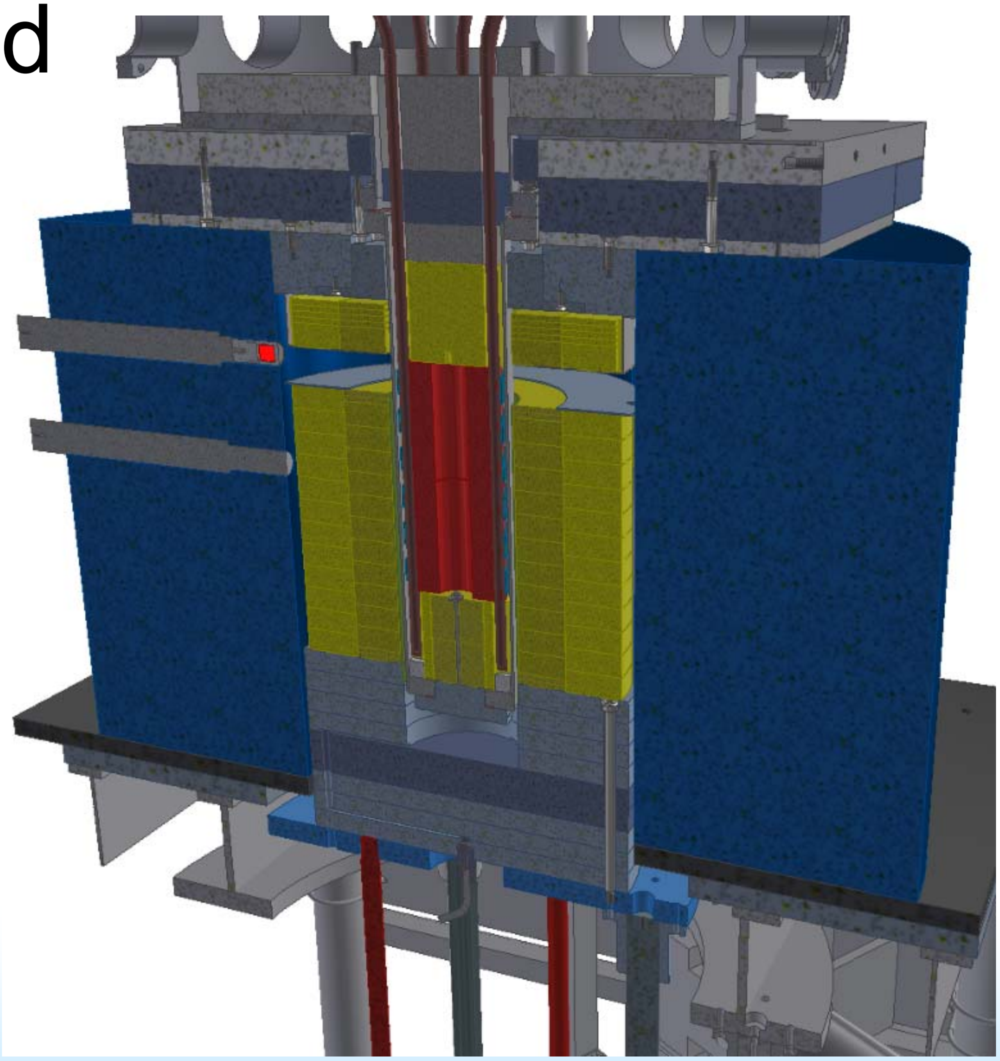
Title: KRUSTY Design and Modeling

Author(s): Poston, David Irvin

Intended for: KRUSTY Program Review

Issued: 2016-11-01

KRUSTY Design and Modeling



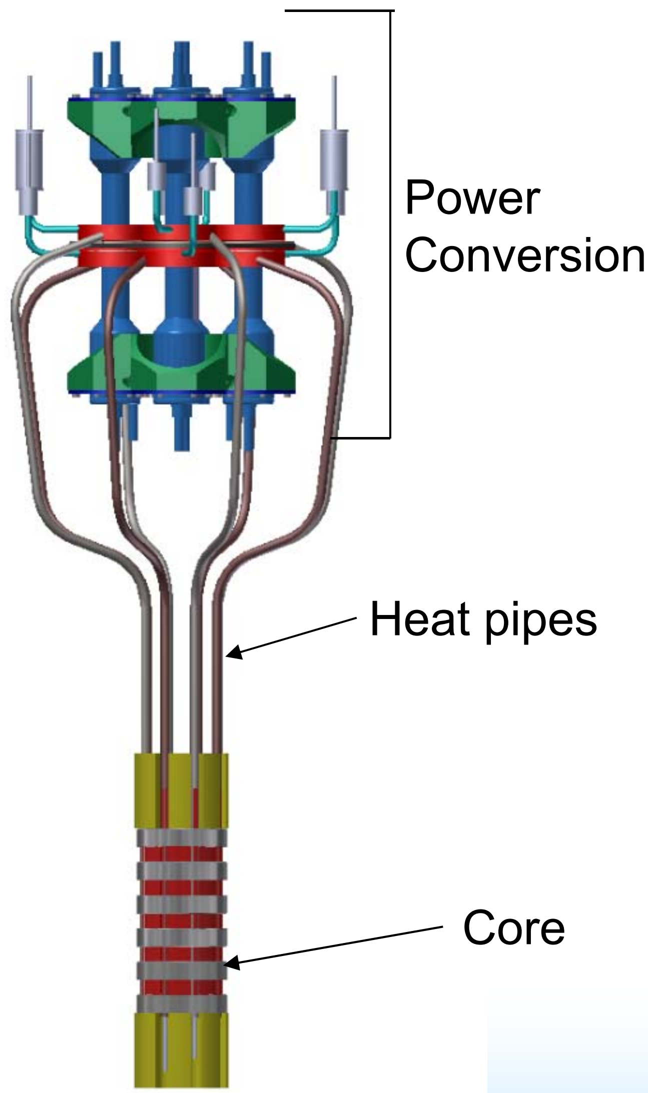
Dave Poston, poston@lanl.gov

This is an ongoing archive of KRUSTY design, modeling and issues. Sections are changed as design changes and/or there are new results.

Table of Contents

Big Picture

- The Kilowatt Reactor Using Stirling TechnologY (KRUSTY) is a nuclear-powered demonstration of Kilopower space reactor concept.
- Kilopower is a NASA/NNSA project to develop the technologies and concepts for space power in the 1 kWe – 10 KW range.
  - There are almost endless reasons why developing a space reactor power system is much easier at these low powers (materials, testing, safety, etc.)
  - Most aspects of Kilopower scale to substantially higher powers (subject of talk last year), and with testing we will hopefully find that the 10 kWe “limit” of is highly conservative.
  - At ~10 kWe it could start to make sense to consider a Brayton Cycle, and of course thermoelectrics can be used to provide lower electric powers with the same reactor.
- History Lesson - if it doesn’t fly it doesn’t scale!!!!
  - To utilize the vast potential of fission power in space we need a path with small steps that is programmatically and technically sustainable.
    - For more, goto spacenuke.blogspot.com

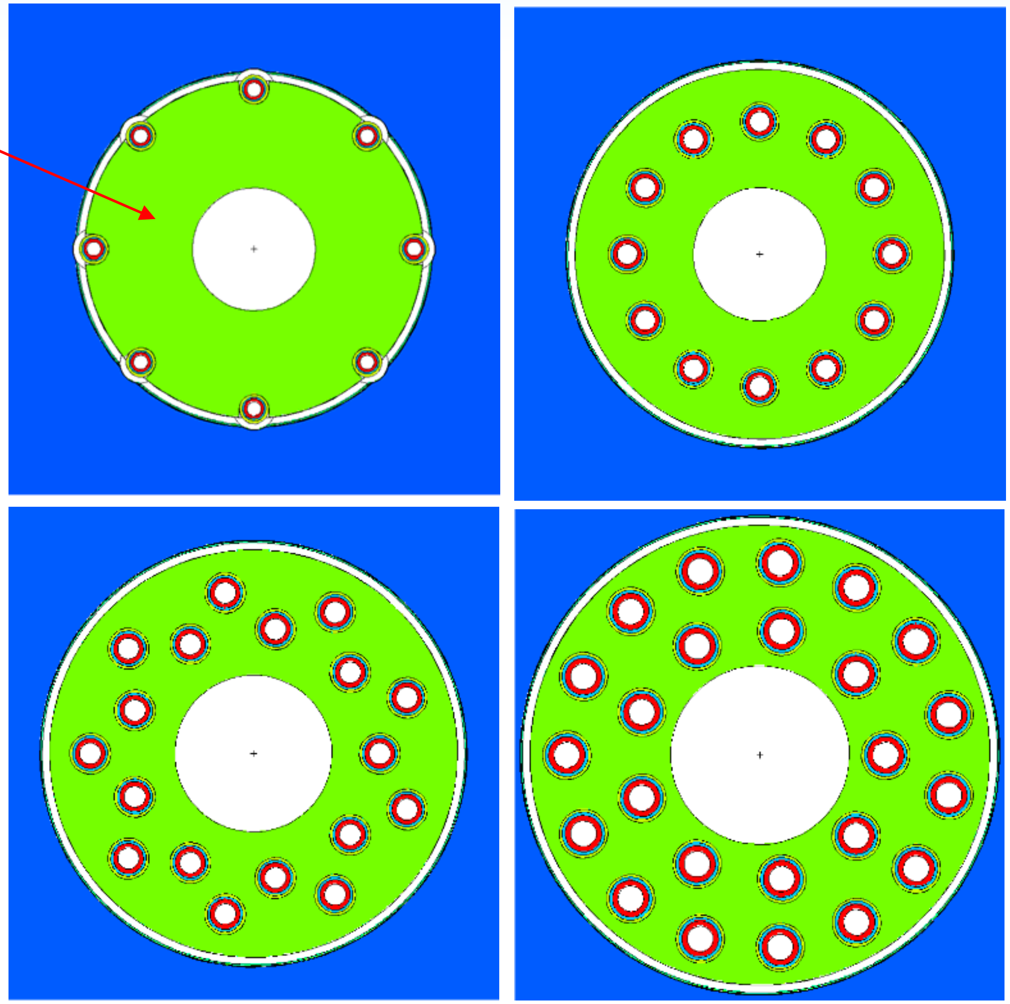


Cross sectional view of proposed Kilopower cores (each schematic is 16x16 cm)

KRUSTY is a prototype of this design

kpwr1a:
4.3 kWt
8 3/8” HPs
U235=28 kg
Reactor=134 kg

kpwr1b:
13.0 kWt
12 1/2” HPs
U235=30 kg
Reactor=158 kg



kpwr1c:
21.7 kWt
18 .525” HPs
U235=33 kg
Reactor=184 kg

kpwr1d:
43.3 kWt
24 5/8” HPs
U235=43 kg
Reactor 226 kg

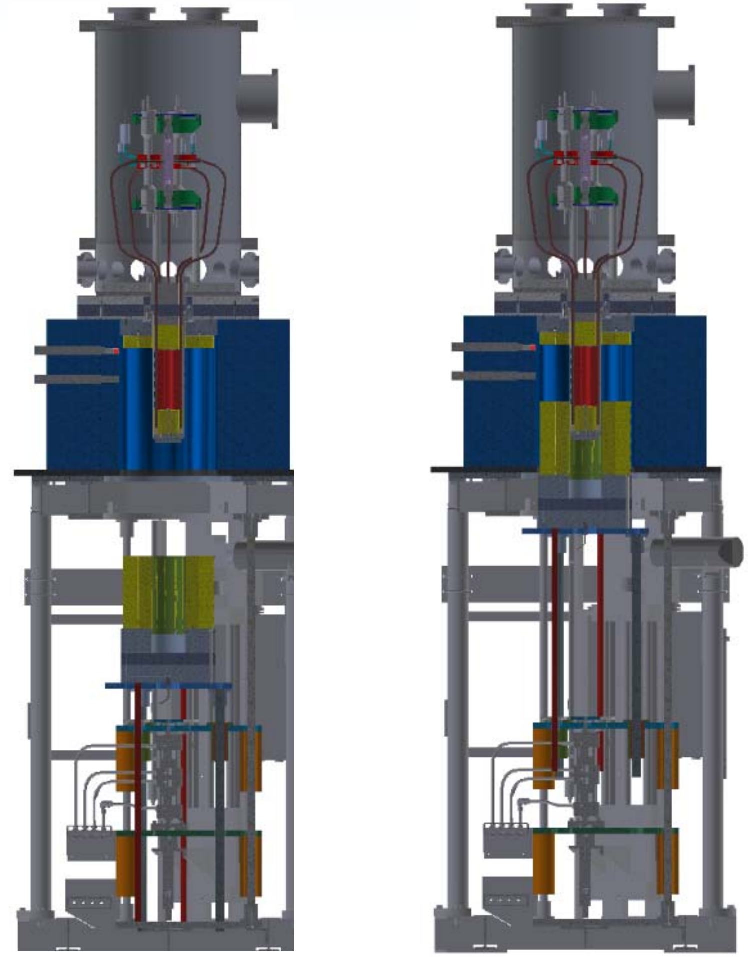
Cores are configured so that failed HP peak fuel temp is similar to 4.3 kWt core
Nominal fuel temps are actually much lower in the higher power cores

(each square is 16x16 cm)

FY-17: Full power ground nuclear demonstration
Kilopower Reactor Using Stirling TechnologY = KRUSTY

- Designed with flight materials/technologies
  - HEU U8Mo core
  - BeO reflector
  - Haynes230/Na heat pipes
  - Stirling converters
- Integrated into flight-like power system
  - Heat-pipe-to-fuel bonding
  - Axial shield integration
  - Bent heat pipes for thermal stresses
  - Heat-pipe-to-Stirling-bonding
- Tested at flight-like conditions
  - Up to 1050 K heat pipe vapor temp
  - Up to 5-kWt steady-state reactor power
  - Prototypic system dynamics/transients
  - Tested in vacuum chamber
- Exercising flight-like infrastructure
  - Design, model, fab, test capabilities
  - Acquire nuclear and material data
  - Zero-power, powered nuclear testing
  - Ground safety issues
  - Transport and assembly issues
  - Integrating the regulators
  - Interagency cooperation

This applies to, and is sorely needed to complete ANY future reactor project.



Platen fully withdrawn. Reactor is highly subcritical with the fuel (red) unreflected.

Platen lifts BeO reflector (yellow) and lower shielding to approach then achieve criticality

Key things missing from KRUSTY: radiator, full suite of Stirlings, startup-rod system, zero-g, launch approval, flight hardware, launch loads, flight qualification, lifetime effects, spacecraft integration.

Initial goals to make KRUSTY the most valuable and "prototypic" to a flight system (in order of importance)

- Core heat transfer, dynamics
  - Ability to demonstrate stable operation and dynamic response of the reactor power system.
  - Ability to determine the load following characteristics of the system.
  - Ability to determine thermal coupling of core to heat pipes, and also coupling of Stirlings to HPs
  - Ability to verify heat pipe performance as part of reactor system, although gravity taints a bit.
- Power
  - Ability to produce and deliver thermal power of similar magnitude and efficiency of flight system.
  - Ability to produce electric power of similar magnitude and efficiency for 1 or 2 modules HP-Stirling modules, and use dummy heat rejection for others via thermal Simulators.
- Core materials
  - All materials as close as flight prototypic as possible, starting with the fuel, then heat pipes, then reactivity control rod.
- Core steady state temperatures
  - Ability to demonstrate thermal, structural, material/chemical and neutronic performance as much as possible
- Reflector material
  - Ability to eliminate neutronic uncertainties that exist with highly reflected beryllium systems (super important, but could be done without KRUSTY)
- Stirling heat rejection
  - Appropriately simulated to give representative dynamic response.
- Core geometry
  - Shapes of pieces resemble flight and similar conduction paths to heat pipes
- Reactor control/startup system/rod
  - Very hard to execute based with low-cost regulatory framework, but fortunately not as important because flight system doesn't have active control, and point-kinetics/system-dynamics is valid with either control approach.
- Reflector temperatures
  - Include reflector feedback/dynamics – less important because substantially slower time constant.
- Shielding
  - Hard to benchmark shielding characteristics with room/equipment scatter, but may try.

KRUSTY Reactor Parameters

UMo	Fuel Material
Haynes-230	Heat Pipe and Core Structure
BeO	Neutron Reflector Material
B4C	Internal Neutron Poison Rod
B4C/SS316	Neutron/Gamma Shielding
5.0	KRUSTY “Rated” Power (kWt)
3.0	Nominal Test Power (kWt)
28.0	Proposed Full-Power Test Hours (hr)
1073	Core Ave Fuel Temperature (K)
~1023	Heat Pipe Condenser Temperature (K)
1.60	Ave Test Fuel Power density (W/cc)
~1.77	Peak Test Fuel Power density (W/cc)
93.10%	U235 Enrichment %
98.50%	UMo Fuel TD %
7.65%	Mo w/o
27.5	Total U235 Inventory (kg)
95.0%	Radref BeO theoretical density
0.00001%	Fuel Burnup (FIMA)
4.7E+15	Fuel Burnup (fissions/cc)
9.3E+11	Core Ave Neutron Flux (n/cm2-s)

“Rated” power (5 kWt) is what the KRUSTY reactor is designed for, but the Stirling engines acquired for the demonstration (due to funding constraints) cannot remove the necessary power, and the Stirling simulators are “limited” as well because they were designed to match the characteristics on the engines (for dynamic demonstration reasons). If all goes well, the 3-kWt testing will show enough margin to verify that KRUSTY could produce 5 kWt or more.

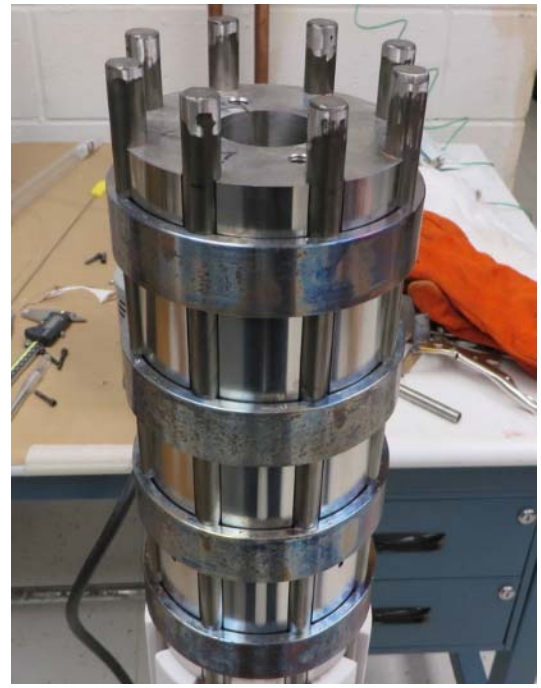
Burnup is calculated over entire proposed campaign, which produces ~80 kWhr.

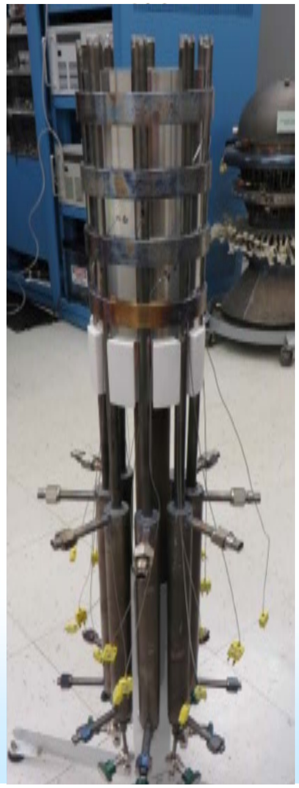
Peak power density does not include an extremely thin (<100 micron) region at the outer edge of the fuel (due to thermal neutrons from reflector). This is discussed later.

KRUSTY: Thermal Prototype

- Vacuum Test
  - Stainless Steel Core
  - Electrically Heated
  - Haynes 230/Na thermosyphons
  - MLI insulation
  - Prototypic Core Can

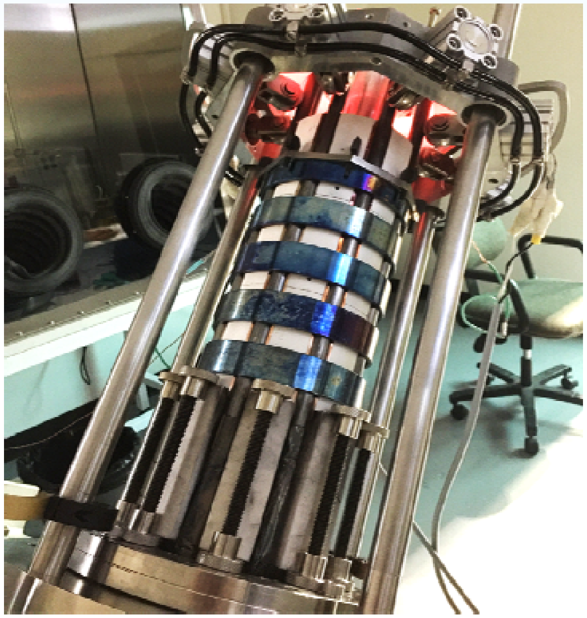
- Addresses
  1. 3+ clamp designs
  2. Core can design
  3. Thermal Interfaces
  4. Creep modeling
  5. MLI performance
  6. Assembly process
  7. Electrical heater





DU Core Thermal Vacuum System Test

- Replace SS316 core section with U8Mo DU core section.
  - The system within the vacuum chamber the same as used in nuclear test – except for heater and fuel enrichment.
- Thermal vacuum system test
  - 800C core operation
  - Haynes 230/Na heat pipes
  - (1) pair of dual opposed ASC modified convertors
  - (3) pairs of Stirling simulators
  - Cold end Ti/H2O heat pipes w/ Al fins
  - KRUSTY core can
- Addresses
  1. Thermal cycling effects of DU
  2. Orthotropic CTE of UMo
  3. Thermal interface verification
  4. DU creep characteristics
  5. Clamp design
  6. Heat Pipe performance
  7. System dynamics
  8. Reactor simulations

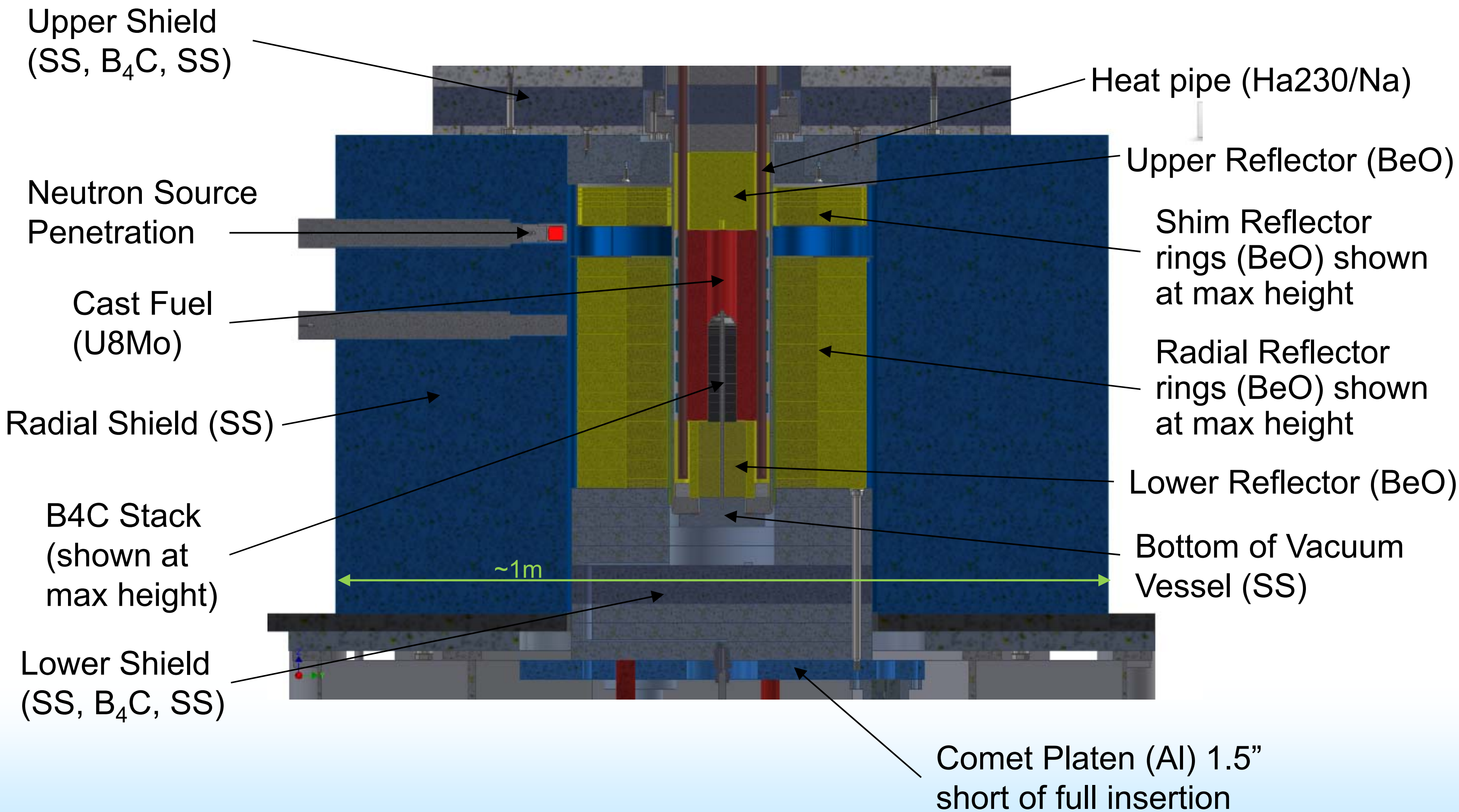


Kilopower / KRUSTY Differences

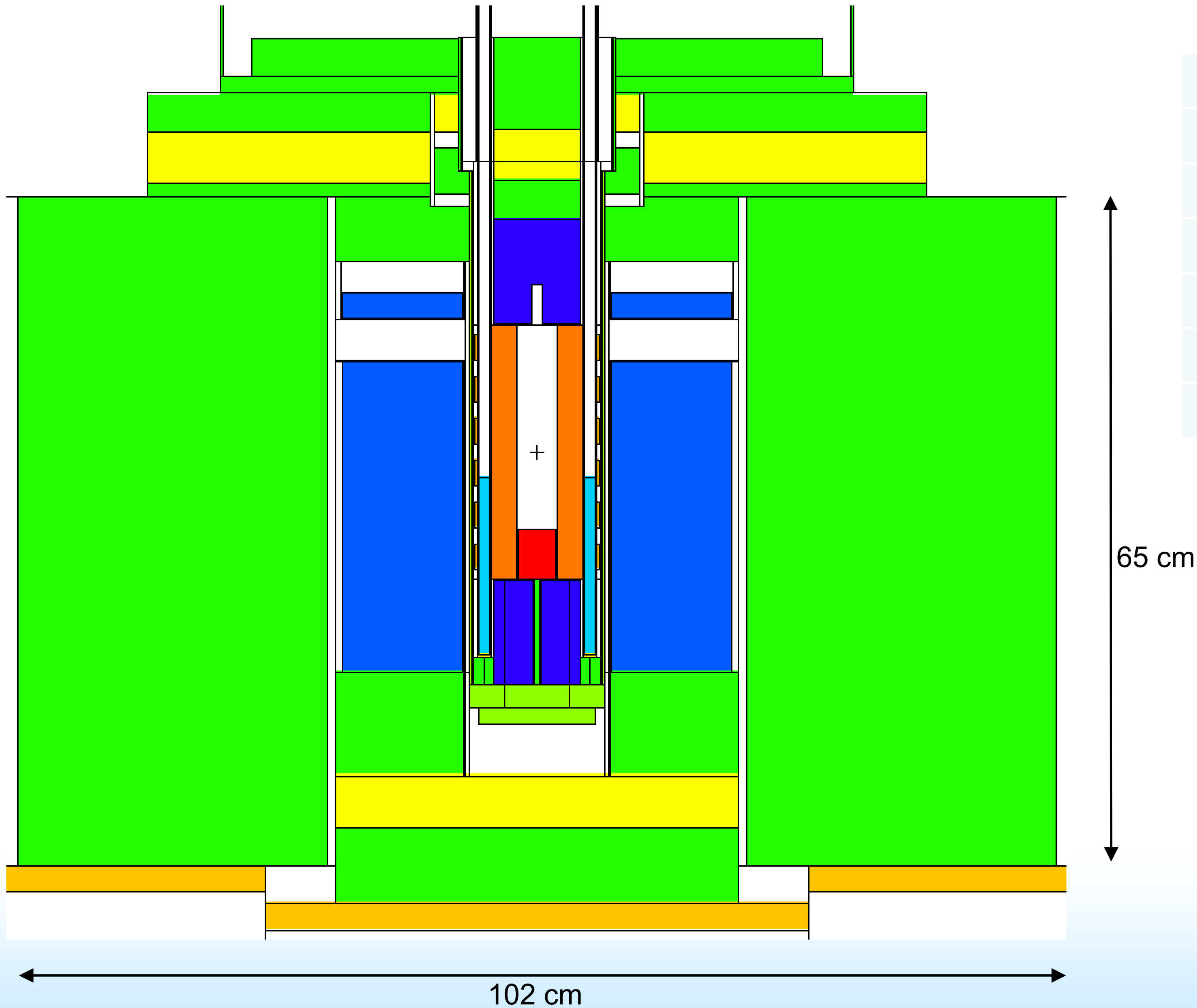
- Differences for the reactor only

	Space 1-kWe Kilopower	KRUSTY	Mars 10-kWe Kilopower
Reactivity Control	Central poison rod	Comet lifts reflector	Central poison rod
Operating time	15 years	48 hours?	12 years
Lifetime Reactivity Control	No	n/a	Yes
Fuel/radref separation	1-mm	1-cm (the Divide)	1-mm
Core can/vessel	No	Yes	Yes
Reference heat pipe OD	3/8"	1/2"	5/8”
Heat pipe thermal bonding	Clamp force?	Clamp force	Braze?
U235 mass	28.4 kg	28.0 kg	43.7 kg
Core Length	24 cm	25 cm	28 cm
Shielding	LiH/DU shadow	SS/B4C 4pi	SS/B4C 4pi
Radref temperature	~700 K	<400 K	~700 K
Gravity	0g	1g	.38g
Space Qualification	Yes	No	yes
Launch safety/approval	Yes	No	yes

KRUSTY Reactor Configuration



KRUSTY MCNP Model



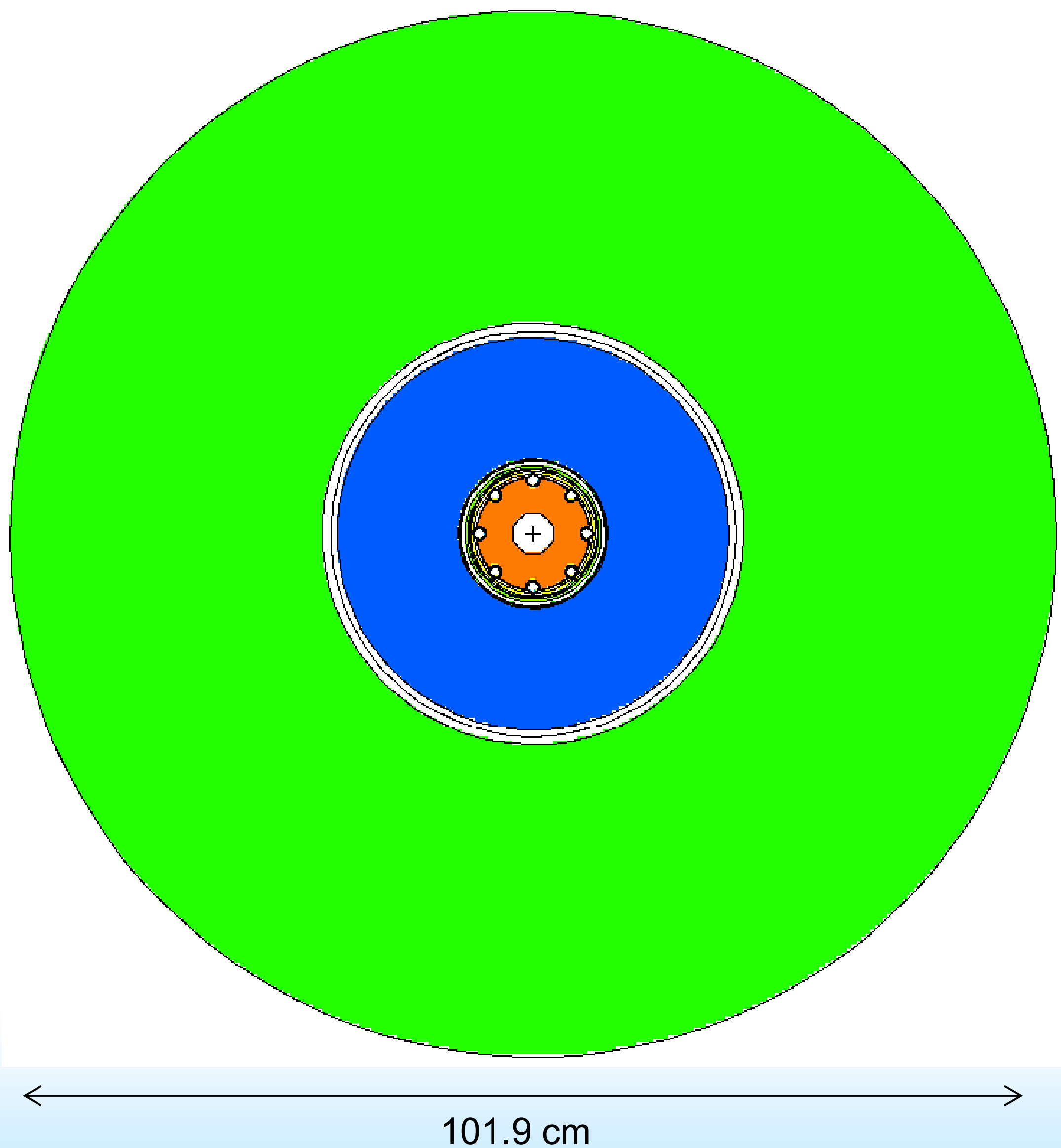
Orange	U8Mo
Blue	BeO
Green	SS316
Red	B4Cenr
Yellow	B4C
Light Orange	Al
Light blue	Na

Na is pool (solid at room temp) which will reduce in height when heat pipe begins to operate.

Central B4C rod/stack (red) is B4C enriched in B10, and yellow B4C is natural.

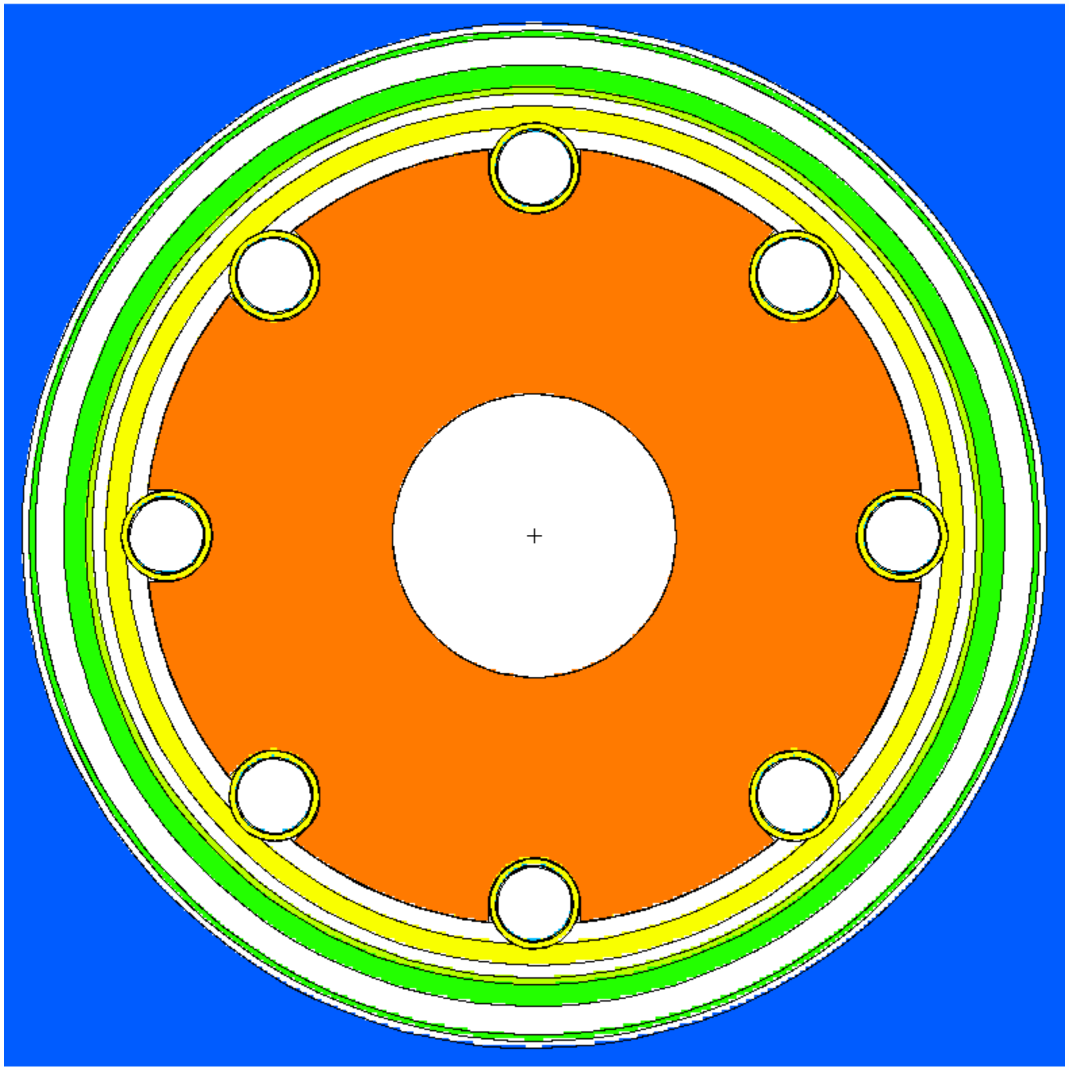
System shown with platen/table withdrawn 3.81 cm (1.5”).

KRUSTY MCNP Model



krst14b	LANL case designator
U8Mo	Fuel material
Mo	Fuel liner material
Hayn230	Heat pipe wall
Hayn230	Heat pipe wick
Hayn230	Clamp Rings (could change)
Na	Coolant
BeO	RadRef Material
BeO	AxRef material
SS316	Vacuum Can
SS316	Radref inner sleeve
B4C	Neutron Shield
SS316	Gamma Shield
38.1	Radref OD (cm)
101.6	Shield OD (cm)

Core Model



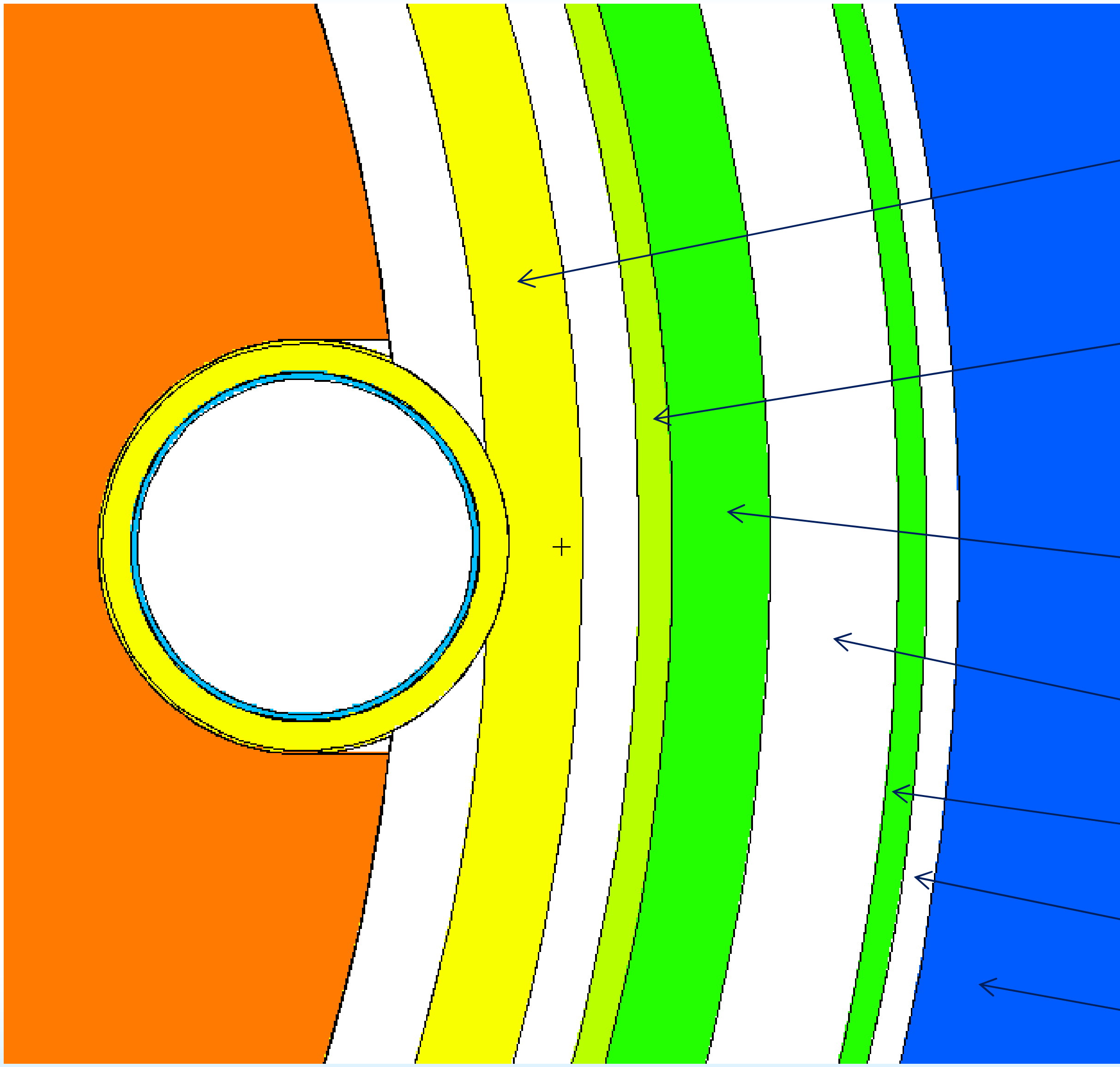
15 cm

Orange	U8Mo
Blue	BeO
Green	SS316
Yellow	Haynes230
Light-Green	Mo multifoil

4.0	Central Hole OD (cm)
11.0	Core OD (cm) 4.33”
10.4	HP “C/L" Dia (cm)
1.295	Fuel Slot Dia (cm) 0.51”
1.270	Heat pipe OD (cm) 0.5"
1.092	Heat pipe ID (cm) 0.035" wall
3.050	VacVes thickness (cm) 0.120"
12.700	VacVes ID (5”)
13.310	VacVes OD (.120” thick)
14.110	Radref Sleeve ID (cm)

Parts modeled at spec – fuel tolerances +/- 0.002”

The KRUSTY "Divide"



3.18-mm Haynes230 Bracket (not a perfect cylinder in reality!)

1.27-mm MLI region: 10 wraps of 1-mil Mo foil with 4-mil spacer/gap
(it will not be this pretty!)

3.05-mm SS Vacuum Vessel

4-mm VacVes-Sleeve gap

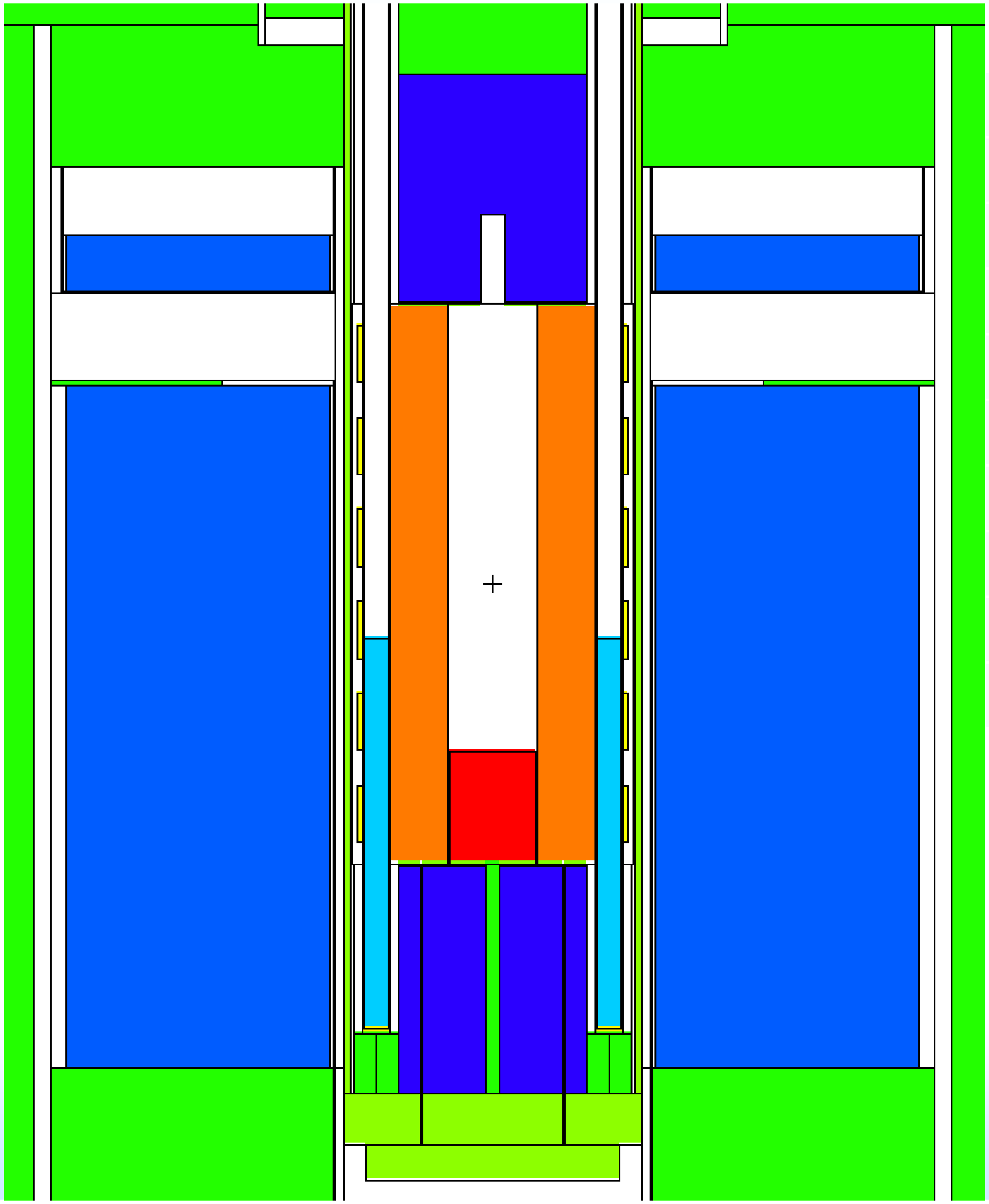
0.89 mm SS sleeve

1 mm sleeve/BeO gap

BeO

Vessel, radref and core all thermally expand freely based on the input temperature to determine reactivity.

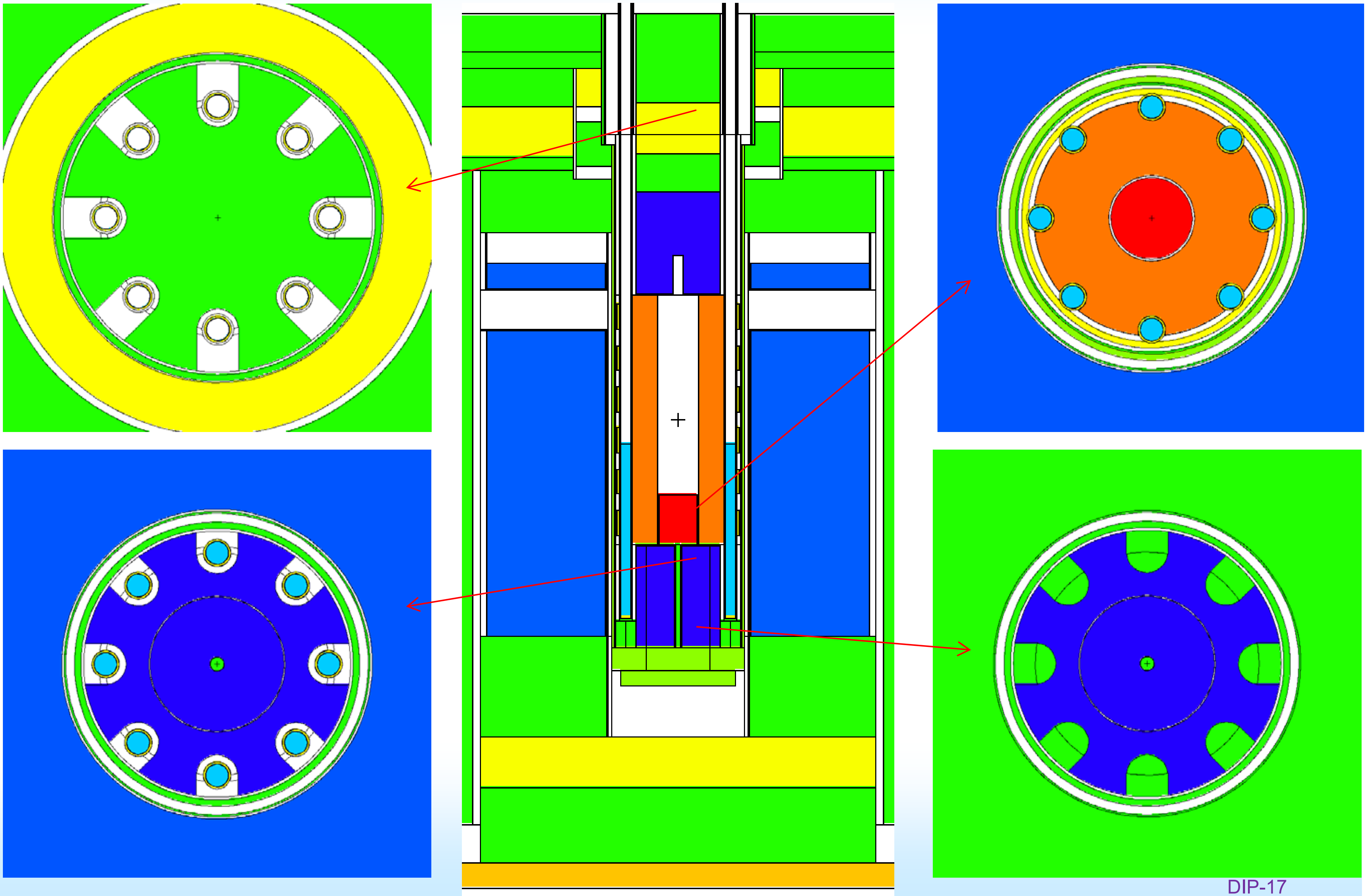
KRUSTY Model



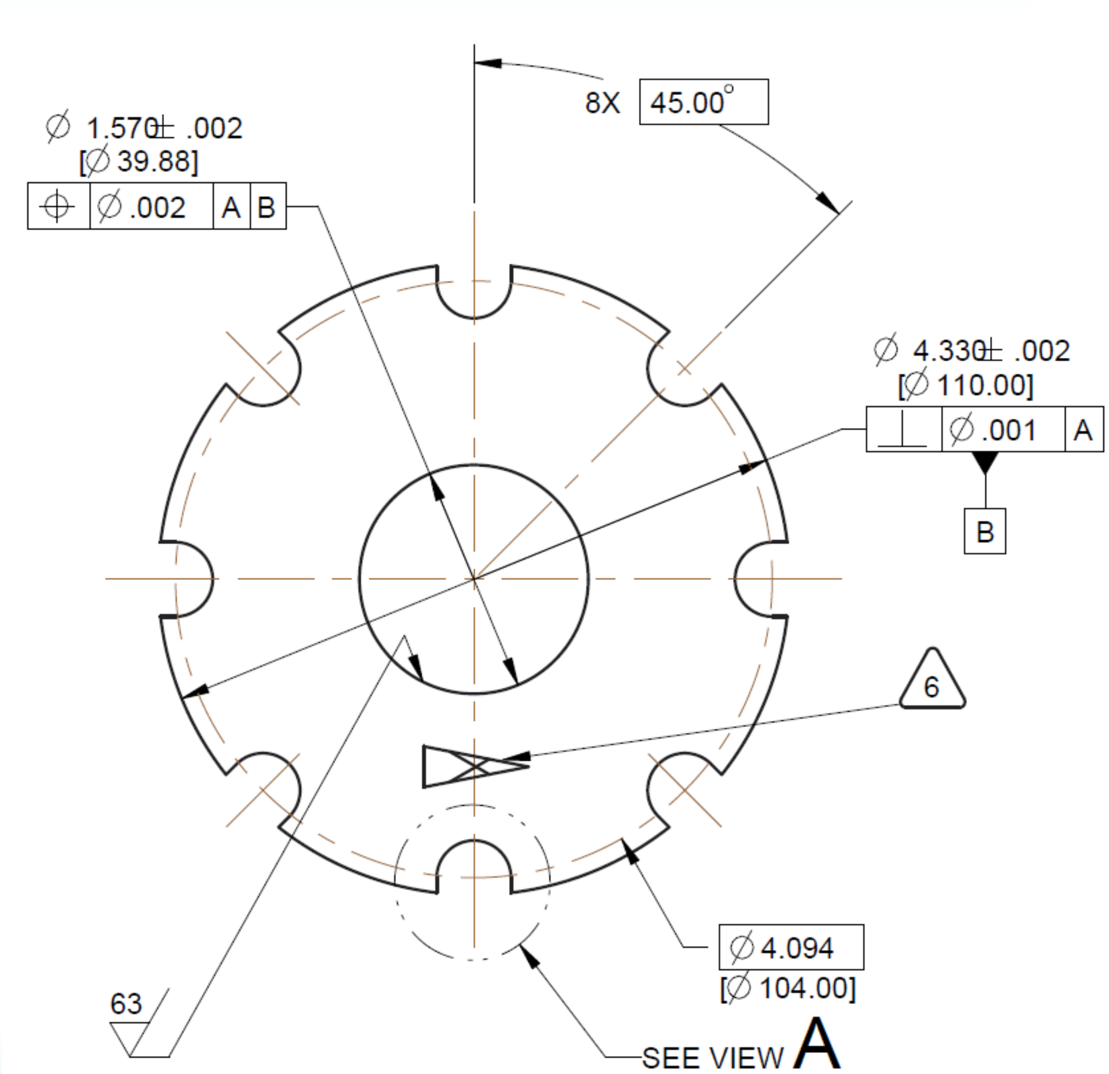
2.62	Fuel core L/D
25.00	Fueled length (cm)
35.56	Maximum BeO radref height (cm)
2.54	Core Clamp height (cm) x 6
1.58	Gap between Core Clamps (cm)
10.16	Top Axial Reflector length (cm)
10.16	Bot Axial Reflector length (cm)
32.1	Fuel mass (kg of U8Mo)
4.3	Axial Reflector mass (kg)
102.6	Radref mass (kg)

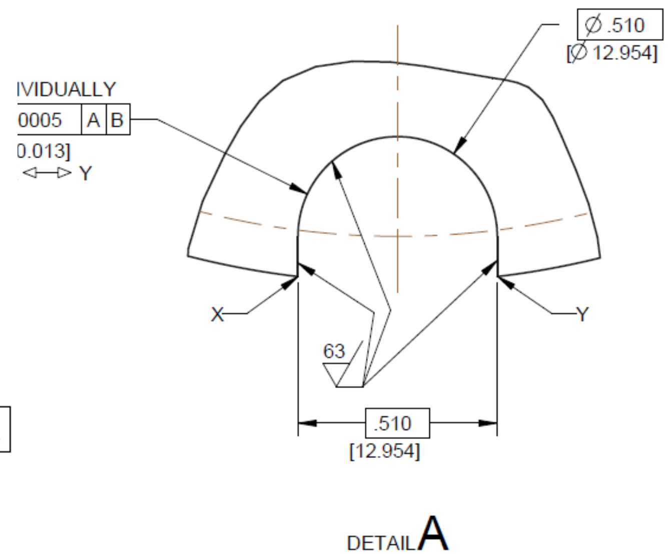
A 0.127 cm region between fuel and axial reflectors contains with 10 layers of MLI (MLI as described on previous slide)

Various Elevations

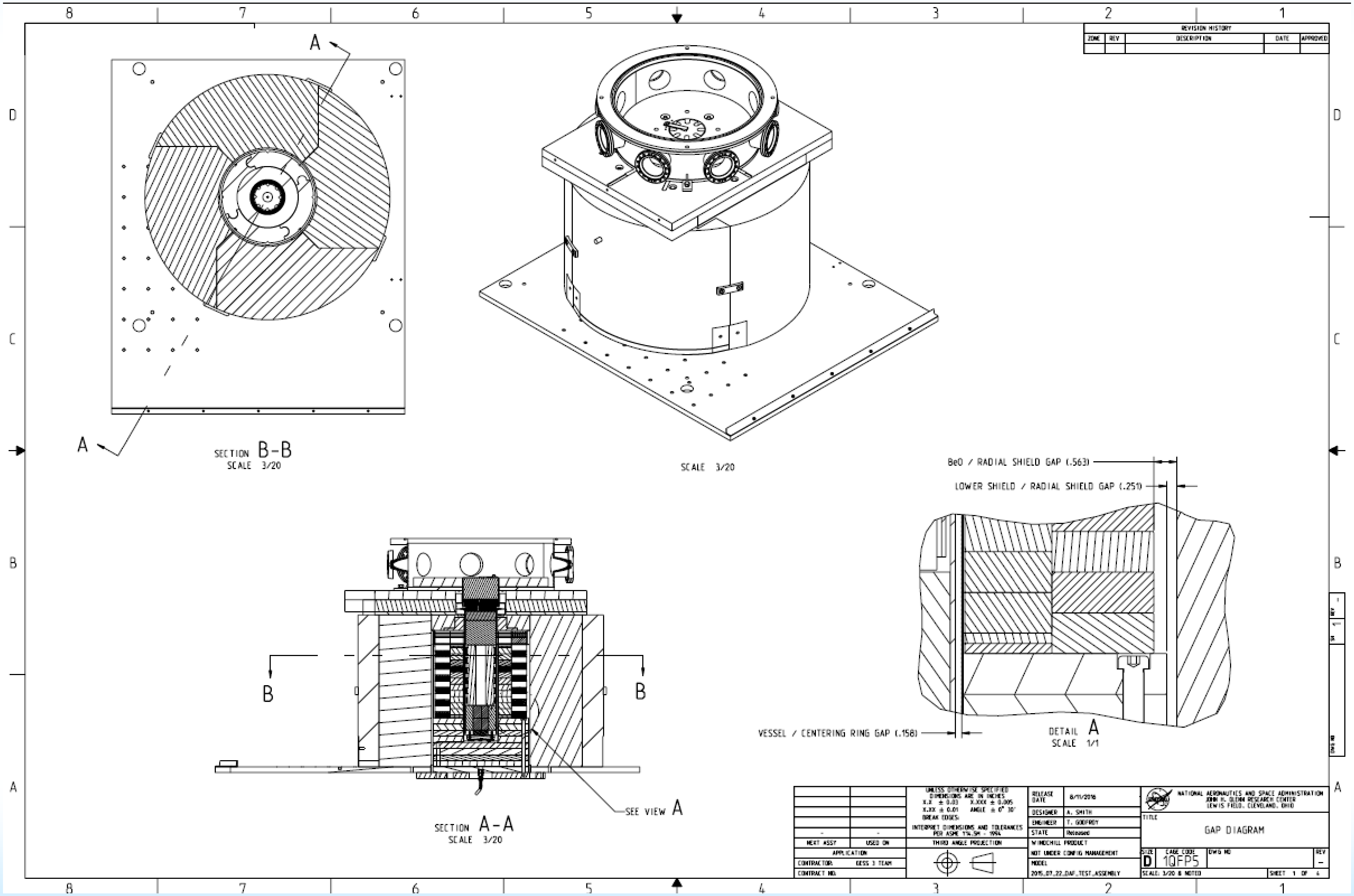


Fuel Drawing

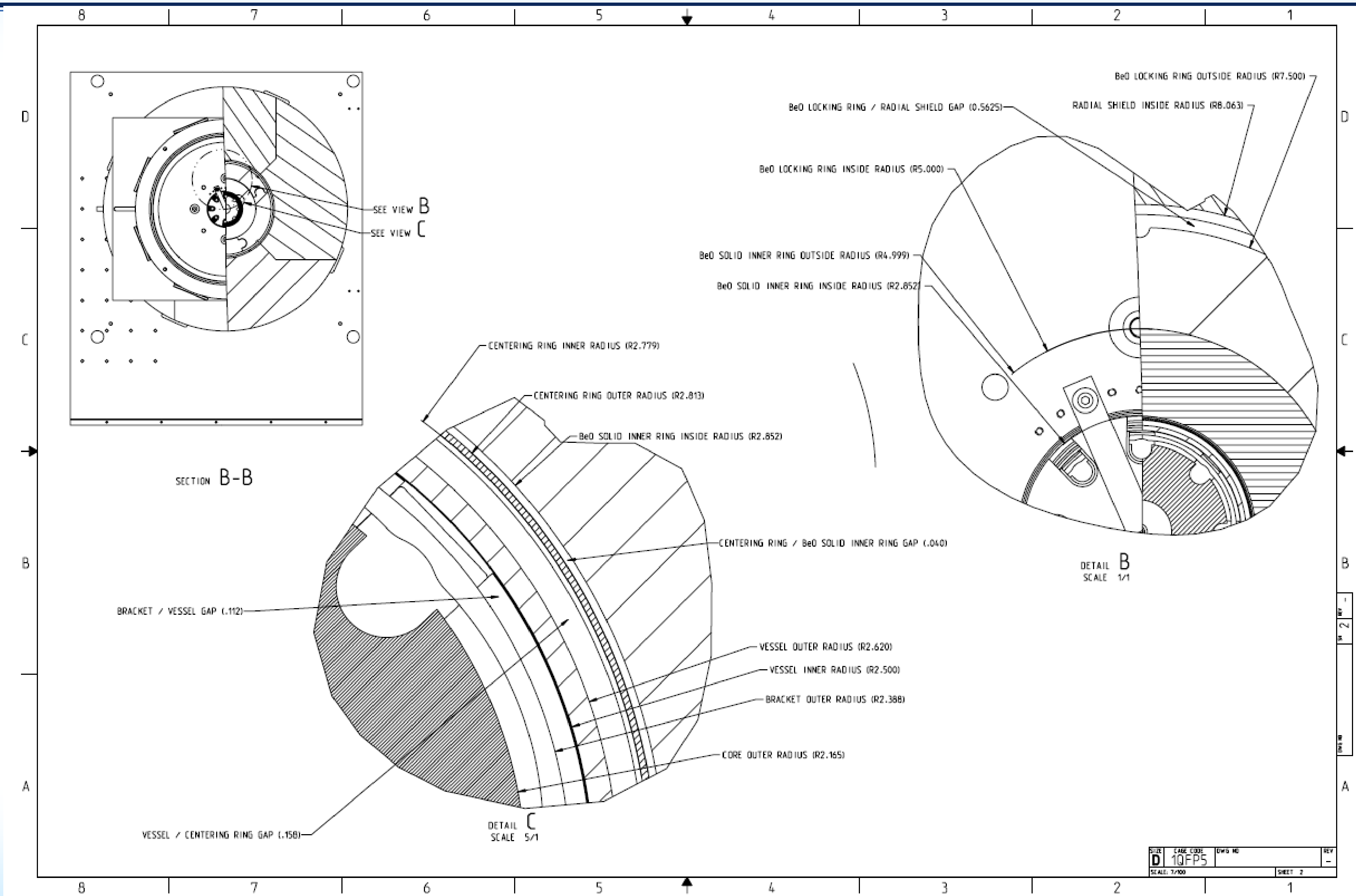




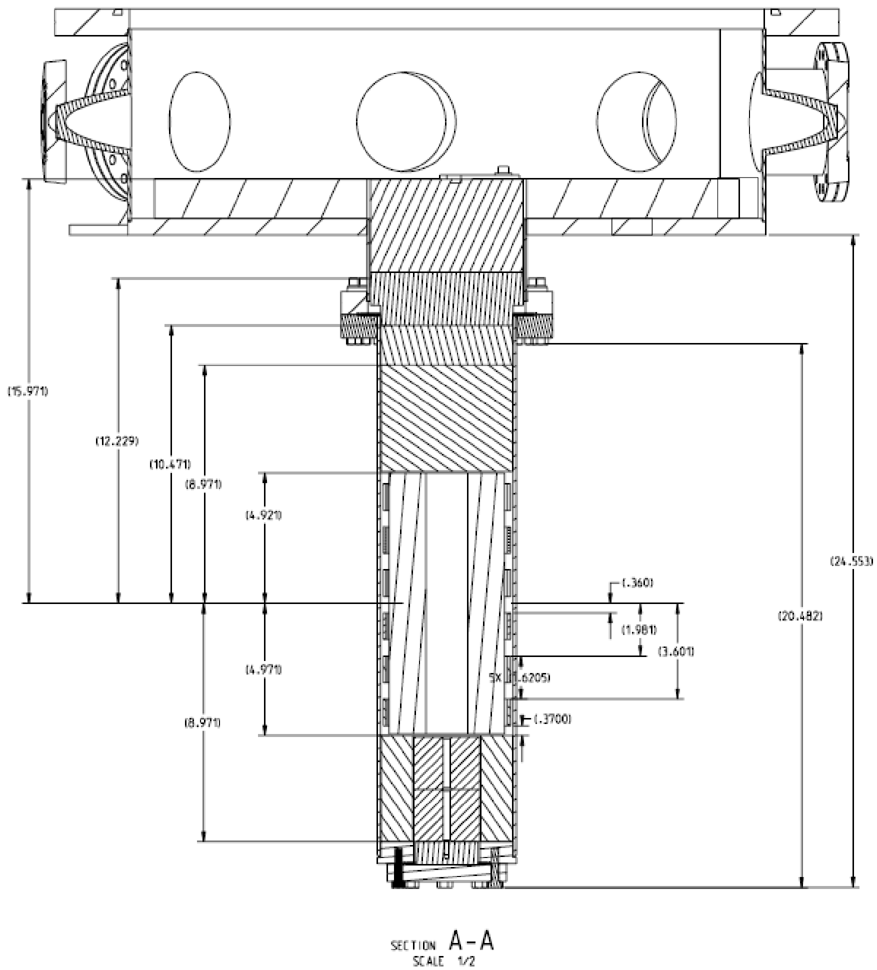
Design Drawings

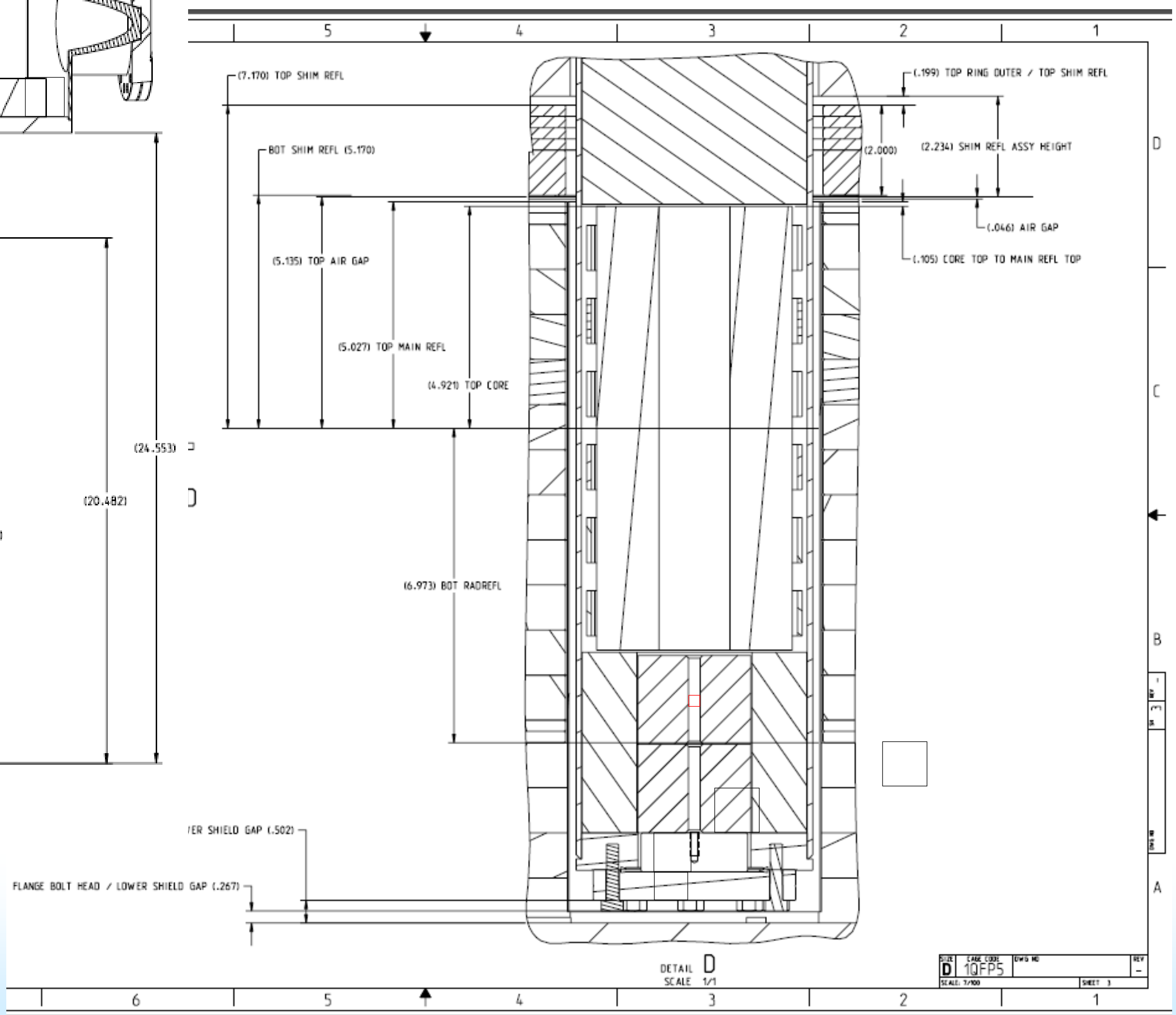


Design Drawings

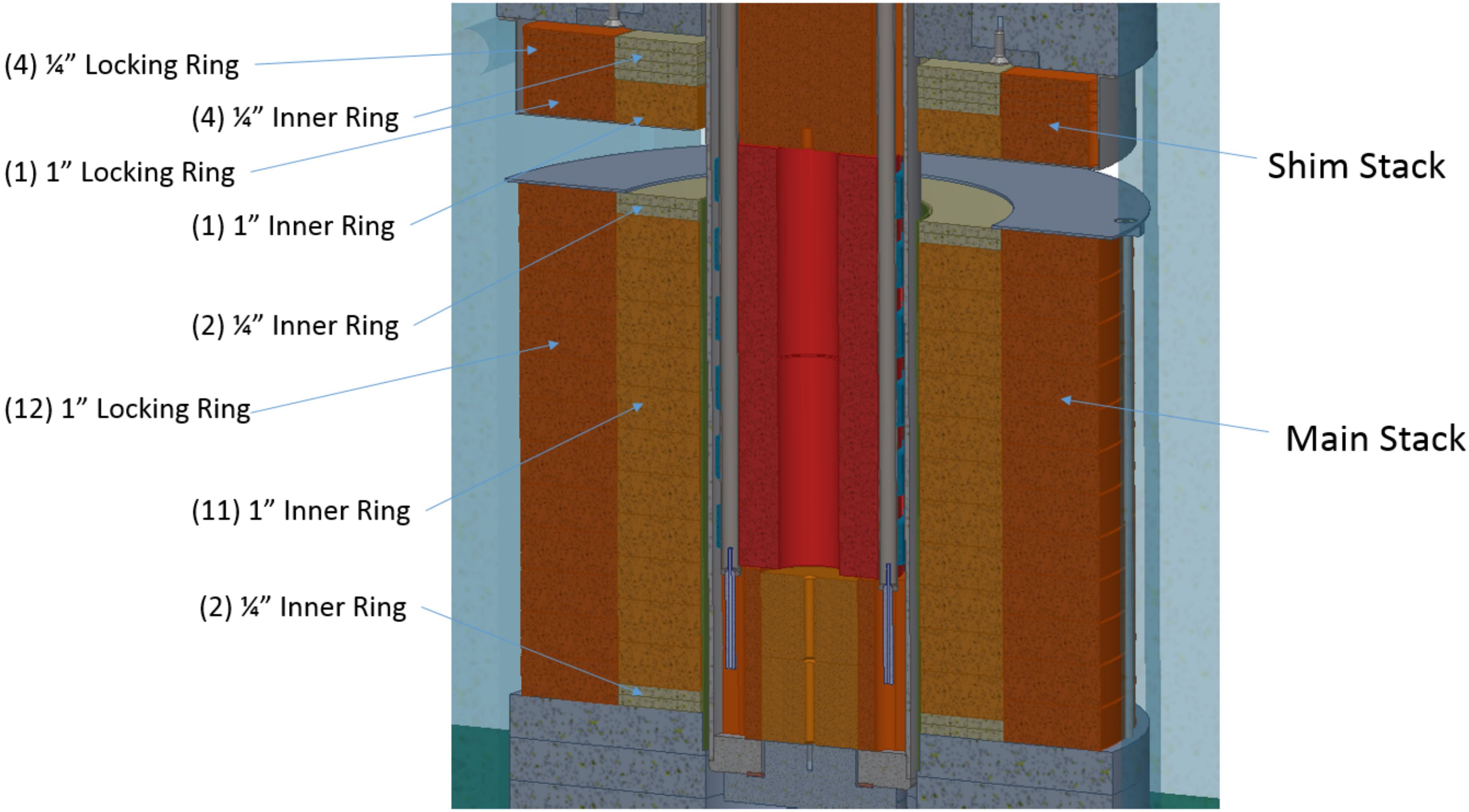


Design Drawings

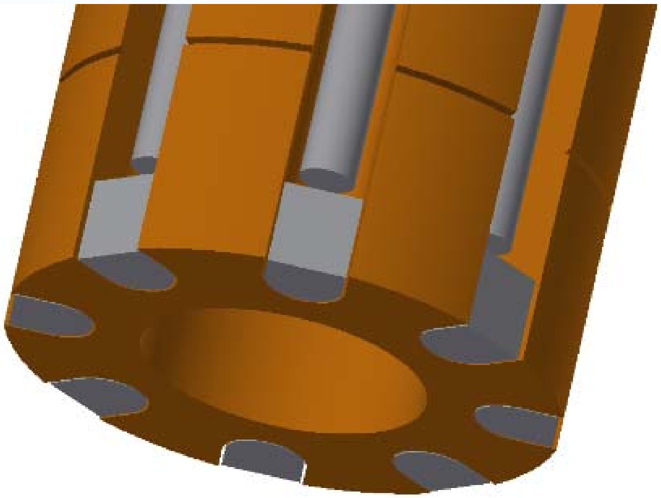


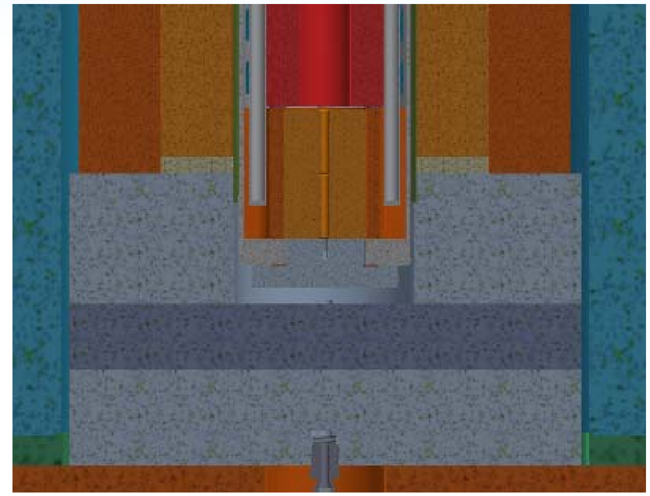


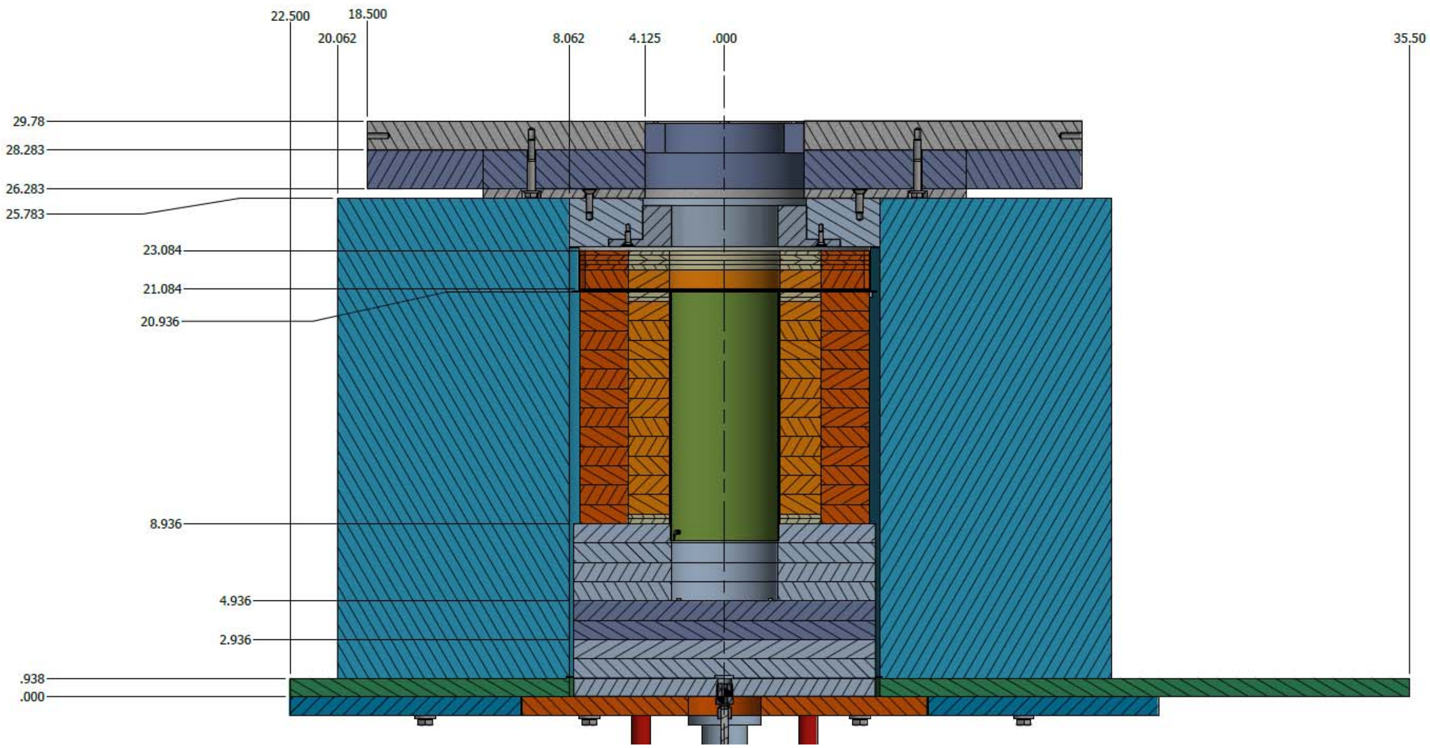
Radial Reflector BeO Stack



More drawings







Tabulation of reactor dimensions

	MCNP KRUSTY DIIMENSIONS - Sep 2016				
surface	cm	in	thick cm	thick in	
721	2.0000	0.787			Fuel IR
411	5.5000	2.165			Fuel OR
1023	5.2000	2.047			HP Ring Radius
270	5.7715	2.272			Bracket IR
271	6.0661	2.388	0.295	0.116	Bracket OR
621	6.3500	2.500			Core Can IR
431	6.6550	2.620	0.305	0.120	Core Can OR
641	7.0563	2.778			RR Sleeve IR
421	7.1452	2.813	0.089	0.035	RR Sleeve OR
441	7.2452	2.852			BeO IR
100	19.0500	7.500	11.805	4.648	BEO OR
110	20.4800	8.063			Shield IR
115	50.9600	20.063	30.480	12.000	Shield OR
	0.5460	0.215			HP IR
	0.6350	0.250	0.089	0.035	HP OR
surface	cm	in	thick cm	thick in	
197	40.567	15.971	8.89	3.5	Top of uppermost plug
187	31.677	12.471	5.08	2	Top od B4C plug
188	26.597	10.471	3.81	1.5	Top of SS plug1
140	22.787	8.971	10.160	4.000	Top upper axref
131	12.627	4.971			Bot upper axref
142	12.500	4.921	25.000	9.843	Top Core
144	-12.500	-4.921			Bot Core
132	-12.627	-4.971	10.160	4.000	Top lower axref
146	-22.787	-8.971			Bot lower axref
346	-25.022	-9.851	2.2352	0.88	Vessel floor
347	-26.658	-10.495	1.63576	0.644	Vessel cap
281	-11.560	-4.551			Bot of bottom bracket
282	-9.020	-3.551	2.540	1.000	Top of bottom bracket
			4.116	1.621	Bracket spacing

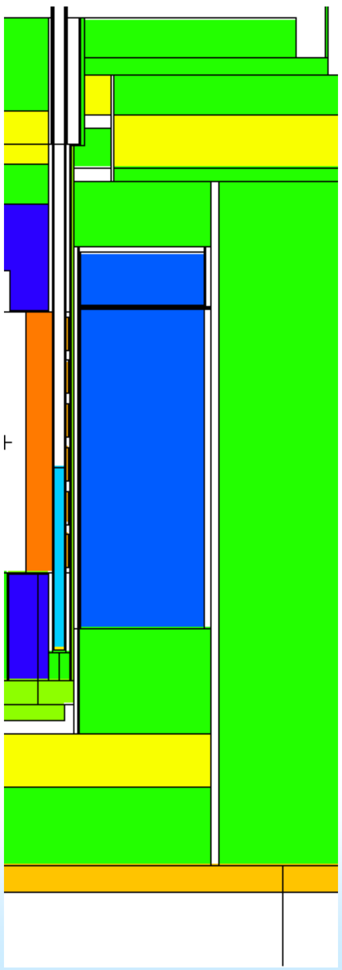
	Ex Core Region relative to platen top surface				
internal shield top	31.905		zchamb	81.0387	
		1.5	internal shield	tshld9	3.8100
vessel top	30.405				
		0.625	vessel bottom	tdeck	1.5875
vessel/shield interface	29.78				
		1.497	SS square	tshld8	3.8024
top B4C square	28.283				
		2	B4C square	tlihz3	5.0800
top mount piece	26.283				
		0.5	SS mount piece	tmount	1.2700
	25.783		zrsh	65.48882	
		2.500	upper wagon wheel	tgamz3	6.3500
bot of up wagon wheel	23.283				
		0.199	gap above shim		falls out
top 2" shim stack	23.084				
		2.000	shim stack	tshim,varies	varies
bot 2" shim stack	21.084				
		0.035	shim can	tpan	0.0889
bot shim can	21.049	2.234		hpan	5.6744
			zpan	53.46446	
		0.050	air gap	gpan	
			zstack	53.33746	
top of clamp	20.999				
		0.063	Beo clamp	tclamp	0.1600
Top of radref	20.936			tstack	30.4800
		12	Radref - zrrbe=12-shortstack	trrbe,varies	30.4800
bottom radref	8.936		zwheel	22.69744	
		4	Wagon wheel	tgamz1	10.1600
Bot wagon wheel	4.936				
		2	Lower B4C shield	tlihz2	5.0800
Bot B4C shield	2.936				
		2.936	Lower SS shield	tgamz2	7.4574
Platen top/shield bottom	0		zcomet - zplat=zcomet-zcrit		

31.905		zchamb = ztopss	81.0387	
	3.5	Top SS plug	topss2	8.89
28.405				
	2	B4C shield plug	topb4c	5.08
26.405				
	1.5	SS shield	topss1	3.81
24.905		zaxhi	63.2587	
	4	Upper AxRef	zref1	10.16
20.905				
	0.05	Upper mli	zaxgap	0.127
20.855				
15.934	9.842	zcenter	40.47236	
11.013				
	0.05	Lower mli	zaxgap	0.127
10.963				
	4	Lower Axref	zref0	10.16
6.963		zaxlo	17.68602	
	0.88	Vessel bottom	zplen	2.2352
6.083				
	0.644	Vessel Cap	zend	1.63576
5.439	26.466	zbves - zchamb-taxves	13.81506	
	0.503	gap when platen fully closed		
4.936	0.502	Drawing says!!!!		
	0.001	DISCREPANCY		
	26.466	taxves		67.22364
	20.344	taxves from top of Rad sh		51.67376

Definition of Table, BeO, and B4C Heights

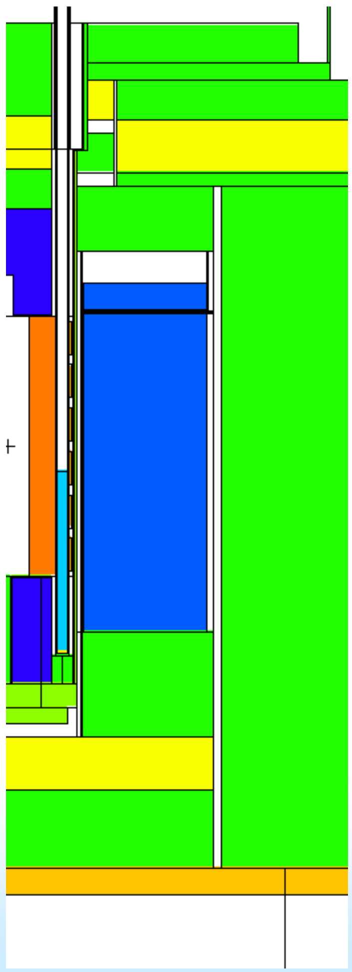
Fully inserted and fully stocked with BeO

zTable = 0.00 cm
zShortstack = 0.00 cm
zShimstack = 5.08 cm
zB4C = 0.00 cm



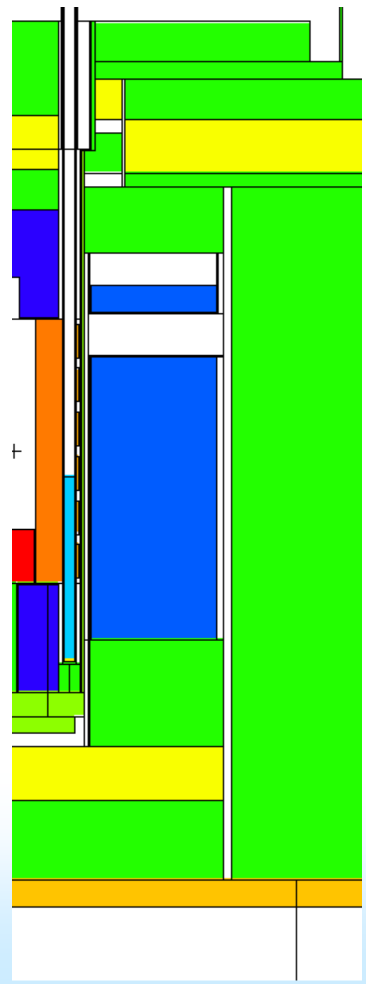
Remove 1" from shim stack

zTable = 0.00 cm
zShortstack = 0.00 cm
zShimstack = 2.54 cm
zB4C = 0.00 cm



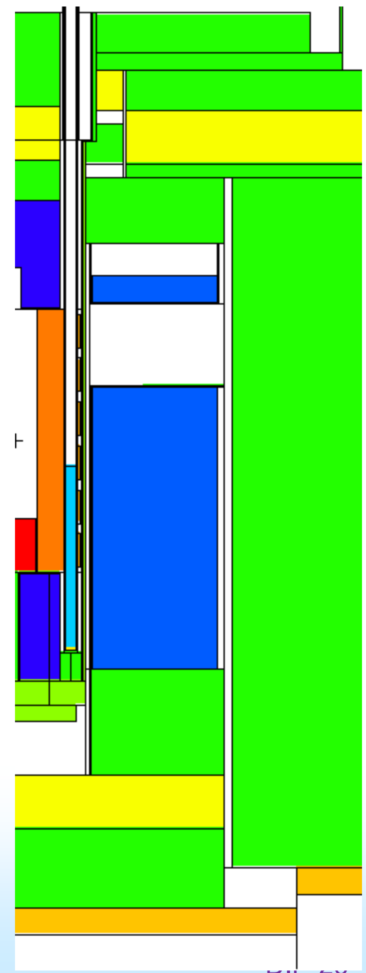
Remove 1.5" from platen stack, add 2" B4C stack

zTable = 0.00 cm
zShortstack = -3.81 cm
zShimstack = 2.54 cm
zB4C = 5.08 cm

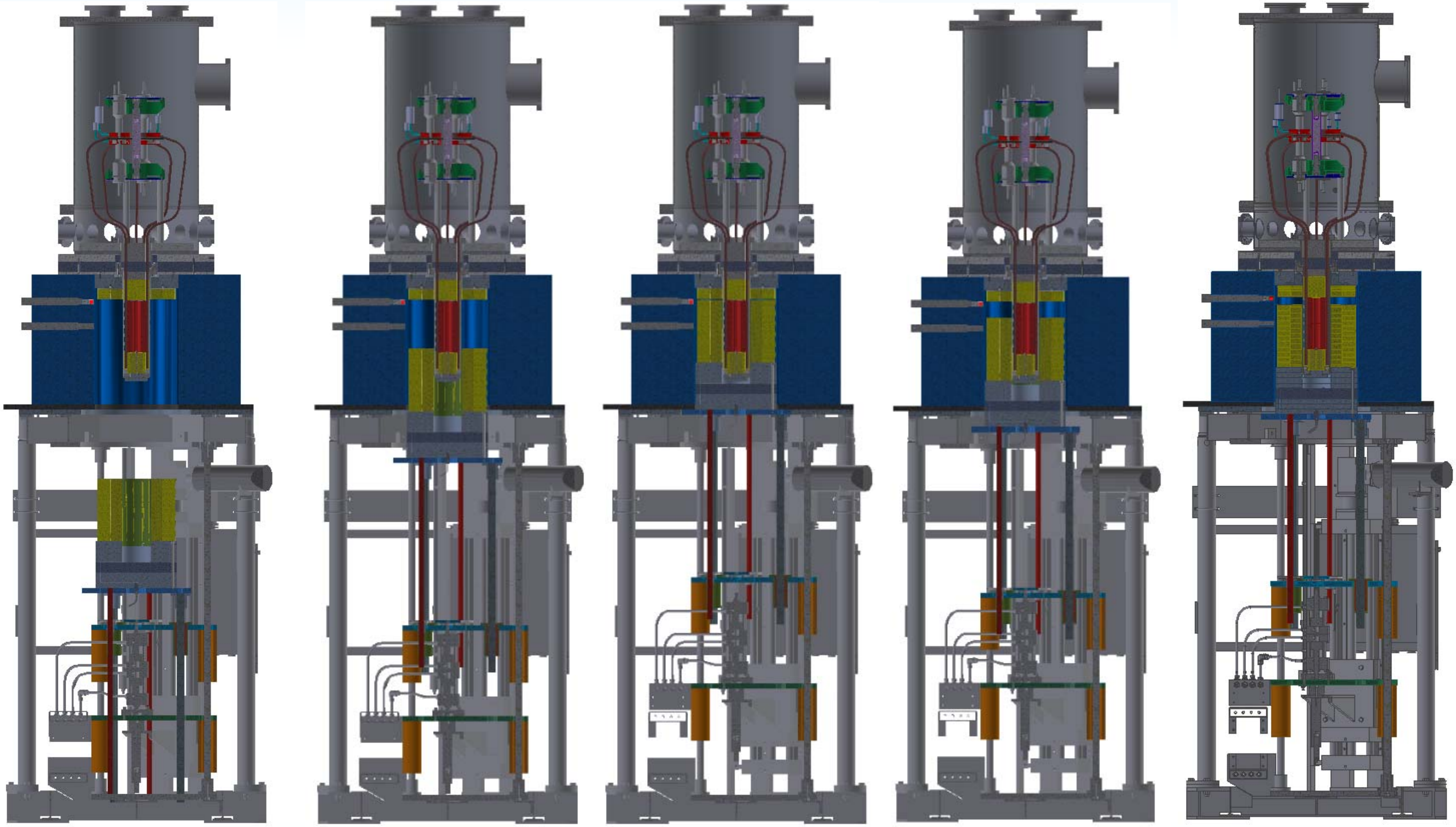


Withdraw platen 1.5"

zTable = -3.81 cm
zShortstack = -3.81 cm
zShimstack = 2.54 cm
zB4C = 5.08 cm



Platen Positions



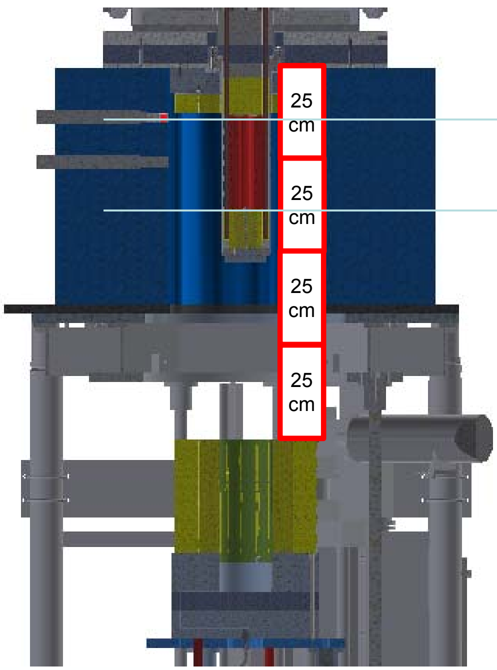
Fully Withdrawn Loading Position	Hand crank, stowed position for full-power testing: “Neutronically” withdrawn	Fully inserted platen, fully loaded with BeO	Fully inserted platen, with nominal 3” scram	Fully inserted platen, with minimum 1.5” scram

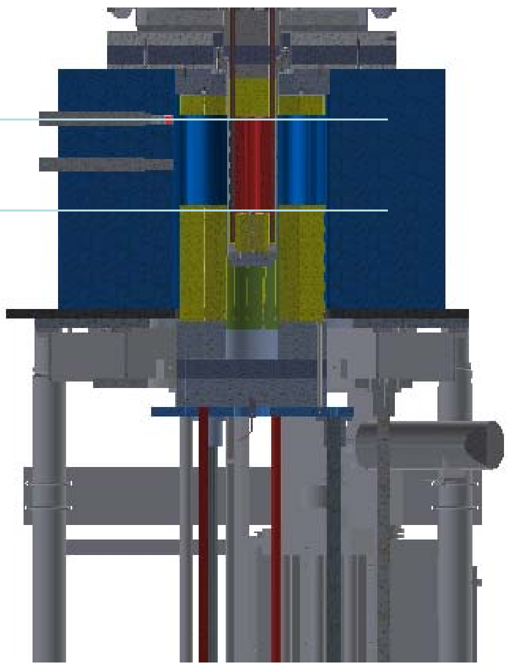
Comparing model and design bulk dimensions

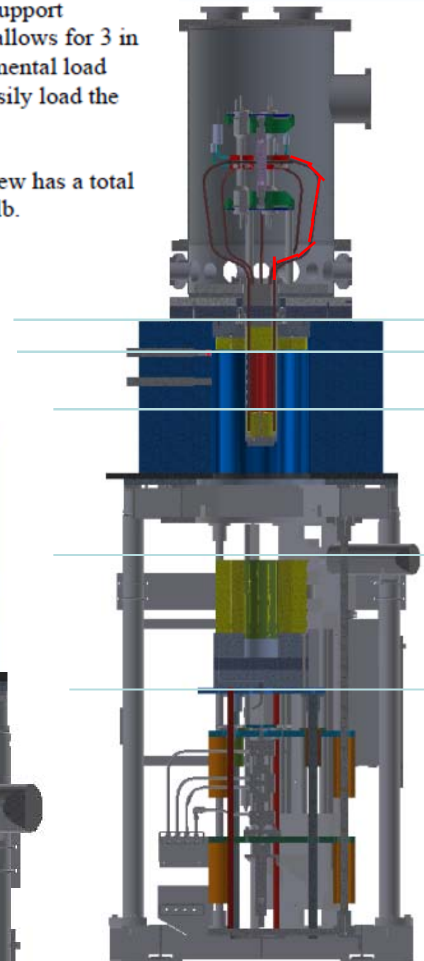
The fixed reference point consists of an accurate scale permanently attached to the Comet support structure. The reference point is located 28 in below the upper core support structure. This allows for 3 in of hydraulic ram travel and 25 in of stepper motor travel before the top of the lower experimental load contacts the upper core support structure. The 28 in of separation leaves enough room to easily load the lower experimental component.

The total lifting capacity of the three jackscrews is approximately 22,000 lb and the jackscrew has a total travel capability of 22 in. The maximum load to be placed on the platen is limited to 2,000 lb.

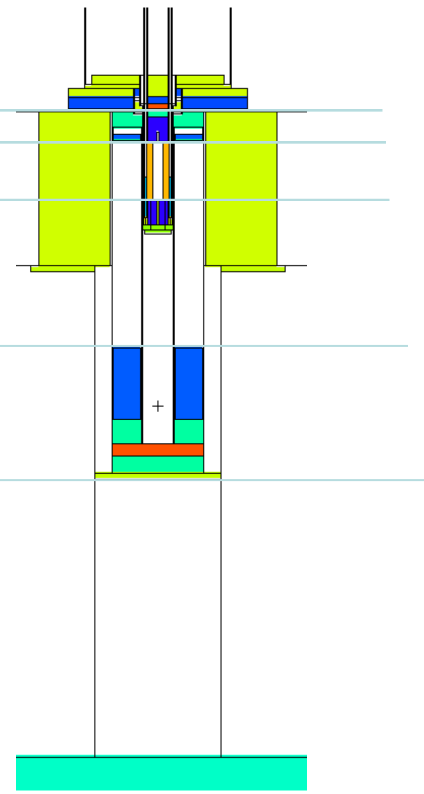
Jack screw 22” = 55.88 cm







=10 cm, estimate 80 cm of HP outside of core



Stowed position ~ 61 cm?
Total travel ~88 cm?

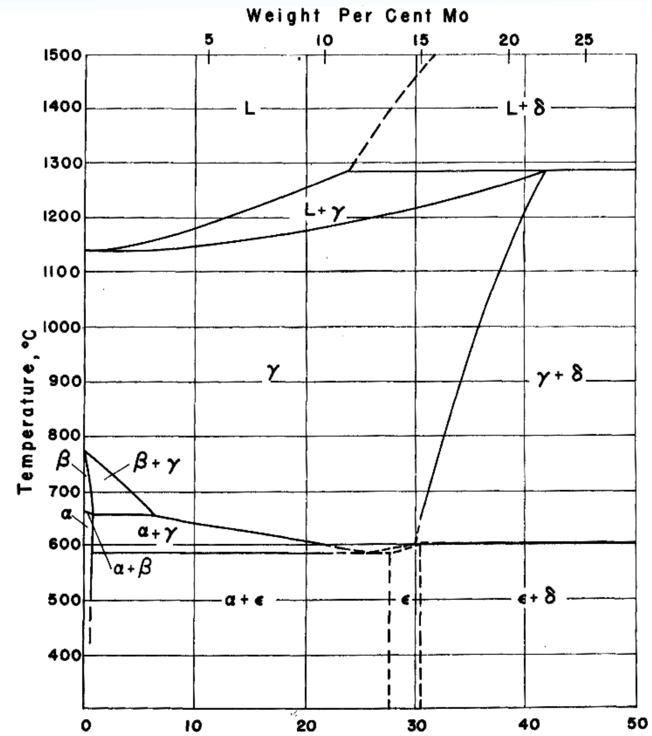
Nominal Modeled Fuel Spec

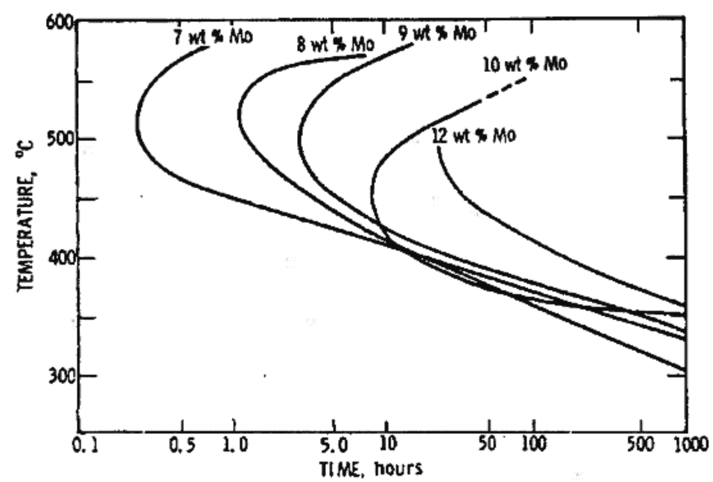
- The nominal KRUSTY model uses a fuel spec that matches preliminary measurements of the DU cores
  - 98.5% Theoretical density
    - Email from Y12 - *we were able to take the rough measurements from the core and the weight. With this we calculated a density. The density of A9ML is ~17.35g/cc. The density of A93E is ~17.32 g/cc. With a theoretical density of 17.5 g/cc, we are at ~99% of the theoretical density.*
    - Assuming19.05 g/cc TD nat U and 12.28 g/cc TD Mo – DU7.5Mo TD= 19.58 g/cc
      - 17.32/17.58= 98.5% TD
    - For HEU 98.5% TD = 17.15 g/cc
  - 7.65% Mo weight percent
    - Slightly greater than any of the DU cores were measured.

	C04K	C0K2	A9ML	A93E	
Top	7.49	7.27	7.55	7.52	
Middle	7.74	7.24	7.57	7.47	
Bottom	7.58	7.5	7.58	7.41	
High	7.74	7.5	7.58	7.52	
Low	7.49	7.24	7.55	7.41	
Variation	0.25	0.26	0.03	0.11	AveofAve
Average	7.603333	7.336667	7.566667	7.466667	7.493333

Why U8Mo?

- Pure uranium would be favorable neutronically (lower mass) and ease of casting, but phase changes could be problematic.
  - It may not be a big deal with limited thermal cycling, and especially space system that only fires up once and stays hot.
    - Electrically heated testing with DU core should expose potentially significant issues.
    - If thermal-cycling is an issue, we may try to keep core hot during all testing at DAF.
      - I.e. we could turn off power conversion system and let KRUSTY "rest" at low power, or continue powered operations overnight.
- U8Mo also has slightly higher strength at elevated temperatures.
- INL and others continue to increase U7-10 Mo experience and database.





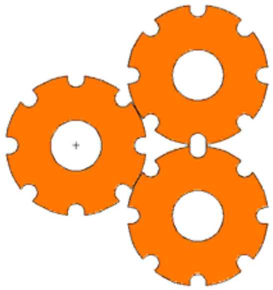
Criticality Safety of Core/Assembly

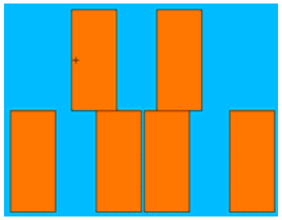
- From a crit safety perspective, the KRUSTY core is neutronically similar to the Flattop HEU core.
- Keff calculations are shown below.

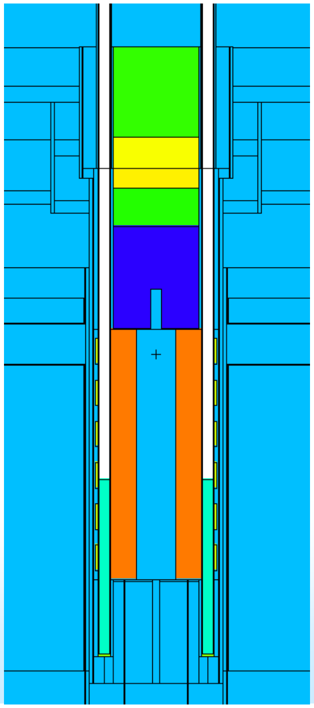
	bare	water	sand	wet-sand
Flattop HEU core ball	0.6576	0.8991	0.8166	0.8863
KRUSTY fuel 1 section	0.4577	0.7642	0.6034	0.7127
KRUSTY fuel 3-section column	0.5886	0.9591	0.8310	0.9346
KRUSTY fuel 3-section triangle pitch	0.5776	0.9710	0.8210	0.9368
KRUSTY fuel 3-section paint-can stack	0.5846	0.9806	0.8296	0.9446
KRUSTY assembly outside of vessel/shield	0.6148	0.9155	0.8311	0.9062
Same as above with central void not filled	0.6148	0.8612	0.8277	0.8881

  - Calculations use pure water and/or 65% pure quartz.
  - All cases are infinitely surrounded and immersed (such that all open voids are filled; e.g. center hole, voids between clamps, mli etc.)
    - Except for the last row in table, which is included to show the effect of not filling the central cavity.
  - The KRUSTY assembly includes heat-pipes, clamps, upper reflector/shielding and mli.

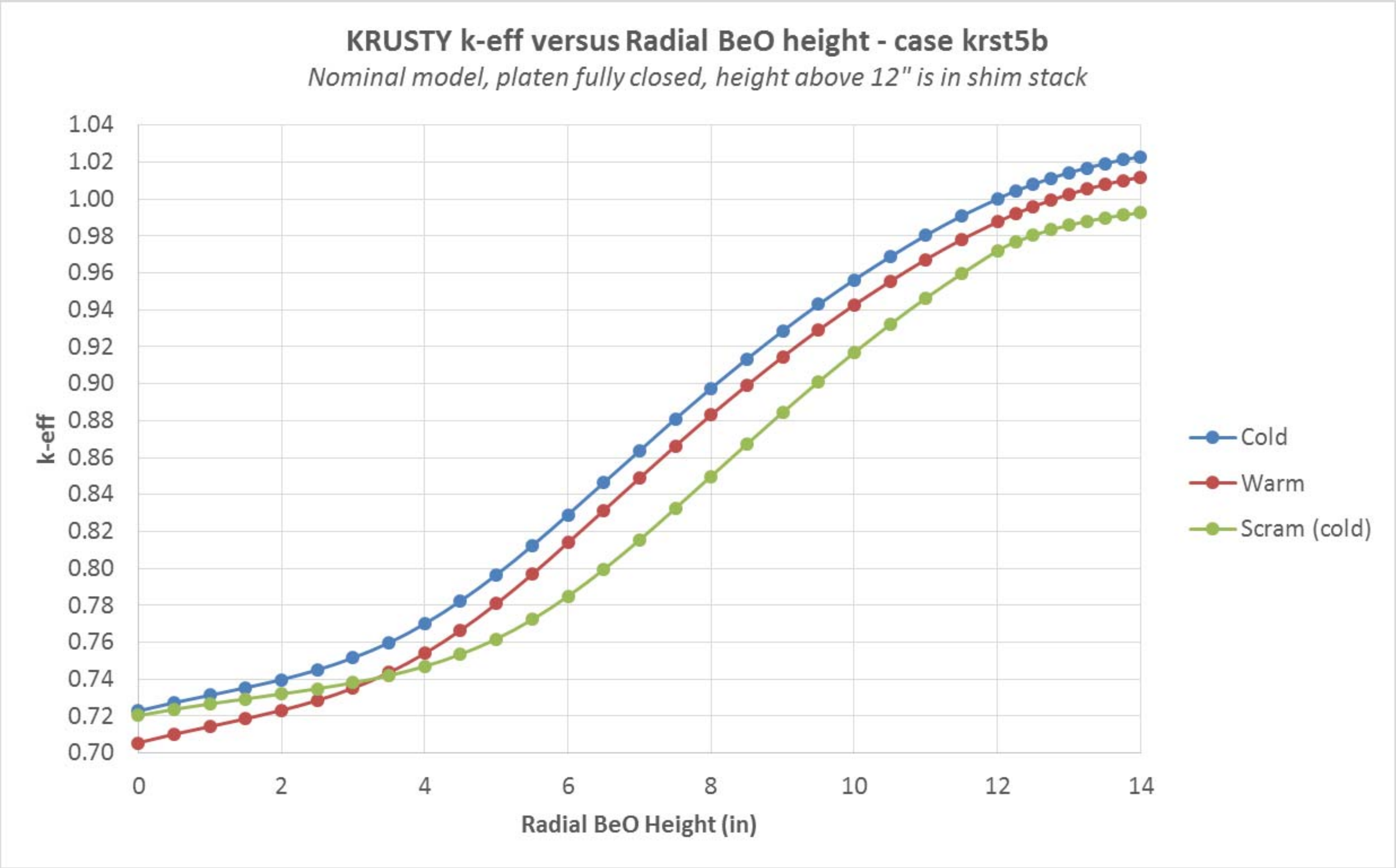
- There is no material that the fuel could be accidentally surrounded by that would take the fuel critical other than Be or another fissile material
  - Academic caveat: a form fitting full (4pi) encasement of >1m thick of high-density/purity graphite could do the trick)







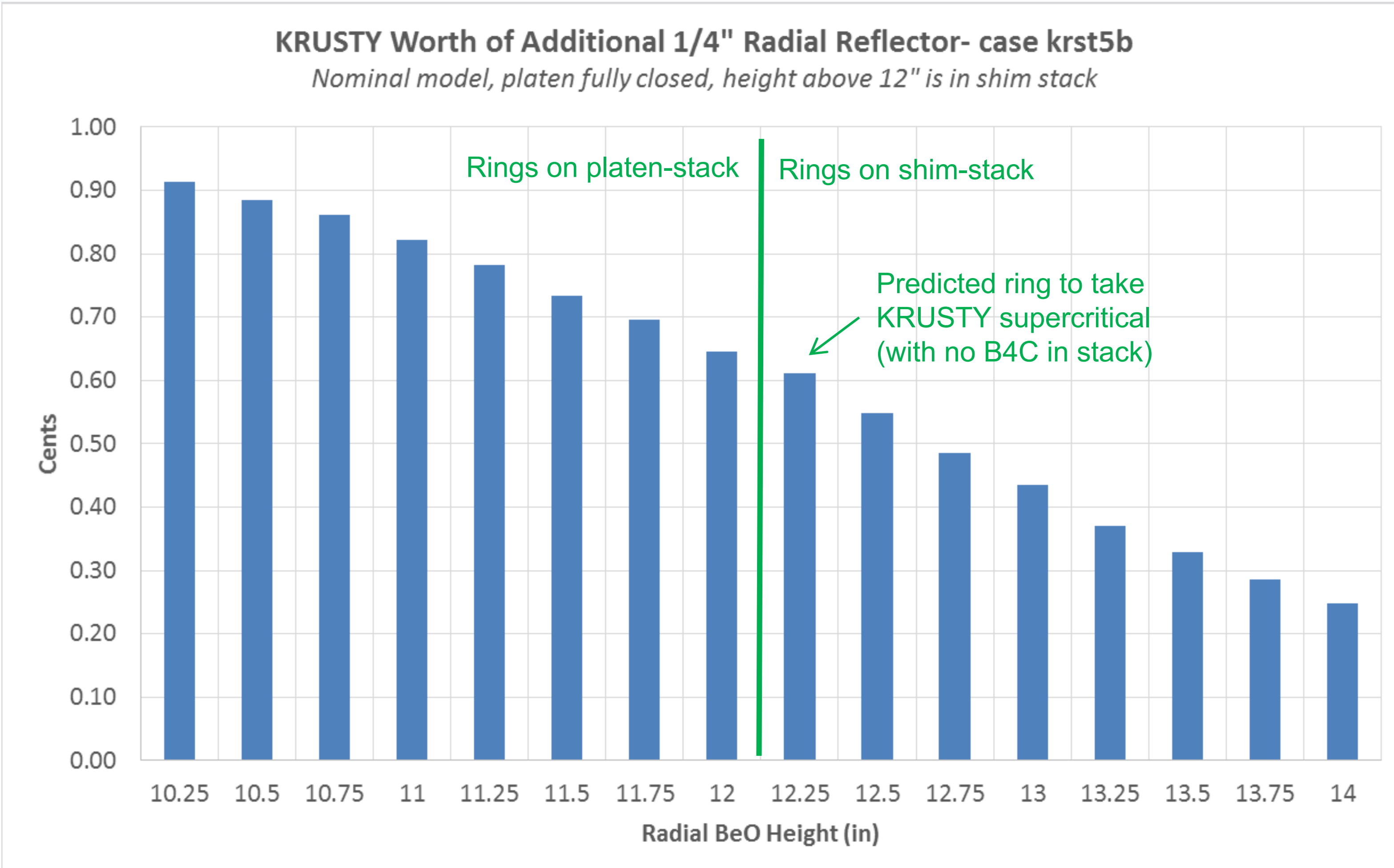
Worth of BeO Stack



KRUSTY will not necessarily be loaded with the entire height of BeO for the powered runs, it will depend on the results of the preceding zero-power criticals, and the use of the B4C-poison stack.

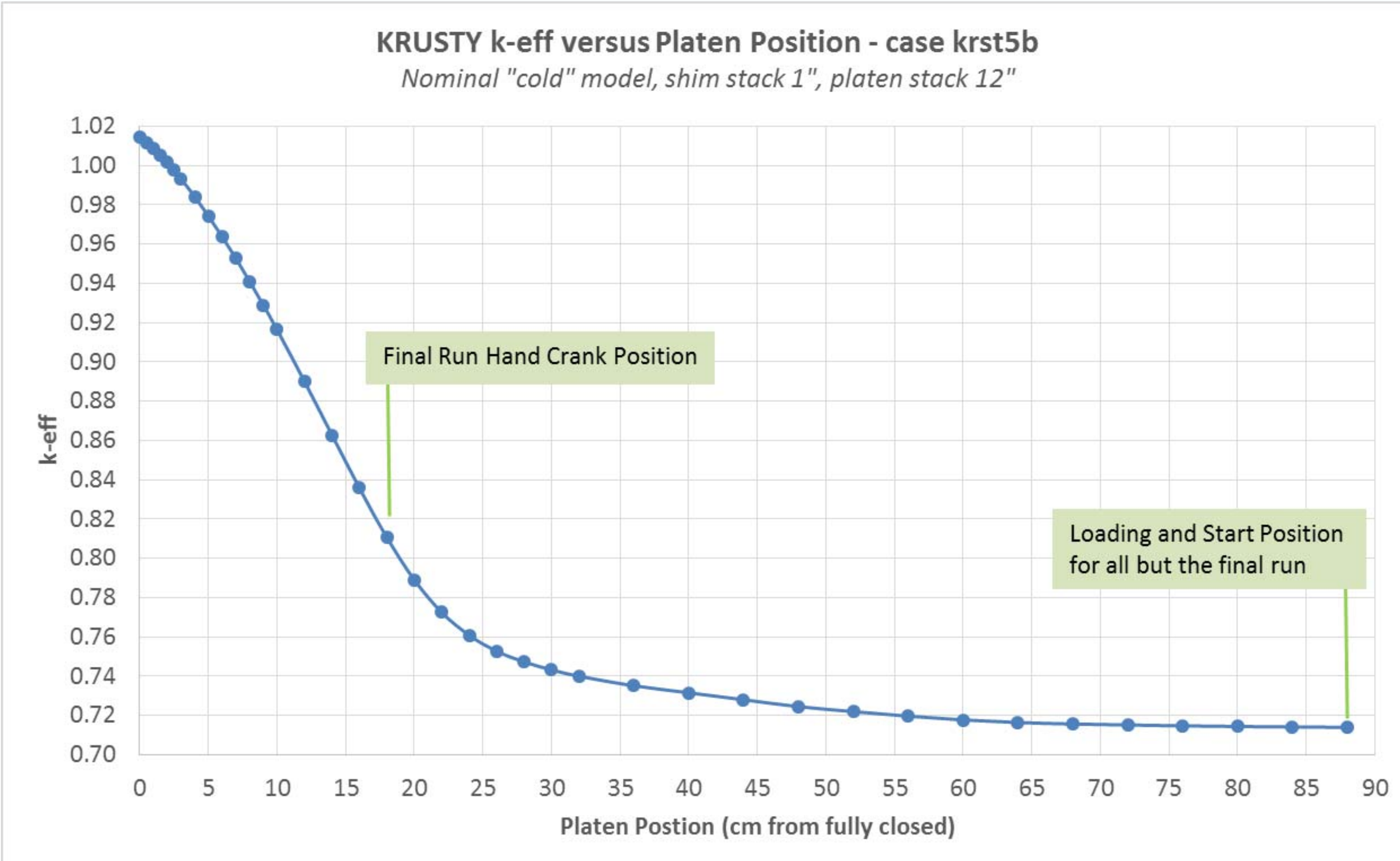
Note: Most charts are presented in metric units, but BeO height is listed in inches because the physical pieces are ¼”, ½” and 1” in height.

Worth of ¼” BeO rings



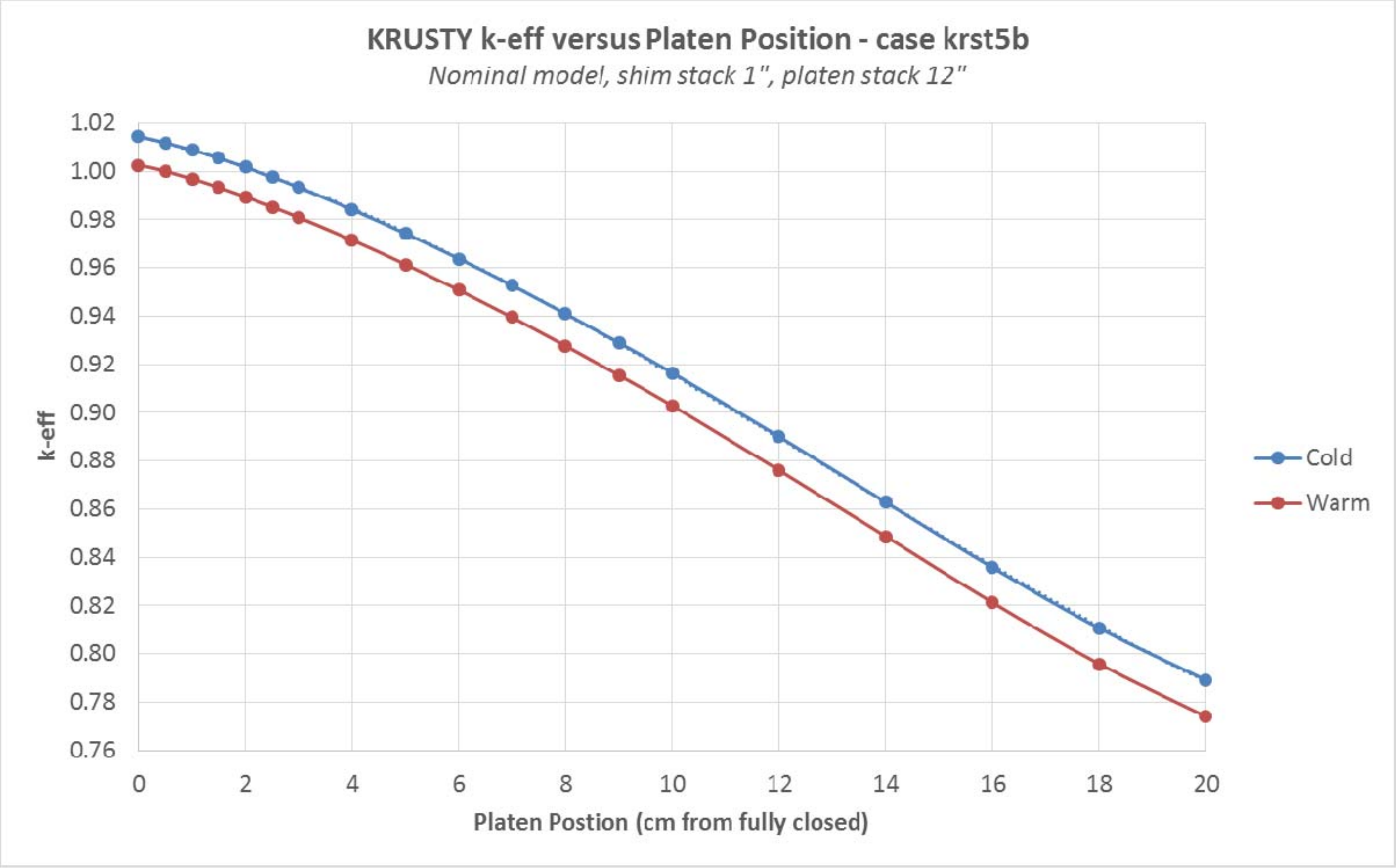
The model predicts cold-critical at 12”, so the worth of the ring that puts us supercritical is the 12.25 ring, which is worth ~61 cents. If there is a very strong negative bias to the model ($2 off, or grossly under-predicted keff), then criticality might occur at ~11.25”, so the first “supercritical” ring could be worth ~73 cents. Also, note that rings are in 4 pieces, the central ring has the vast majority of the worth, but using the central ring without the outer ring segments would allow a slightly smaller incremental worth. Also Al rings will be available to produce smaller incremental worth. Note, the platen stack ends at 12”, the first ring in the platen stack is at 12.25” - a slight discontinuity in the worth trend can be seen there because of the gap.

Keff versus platen position (nominal model)



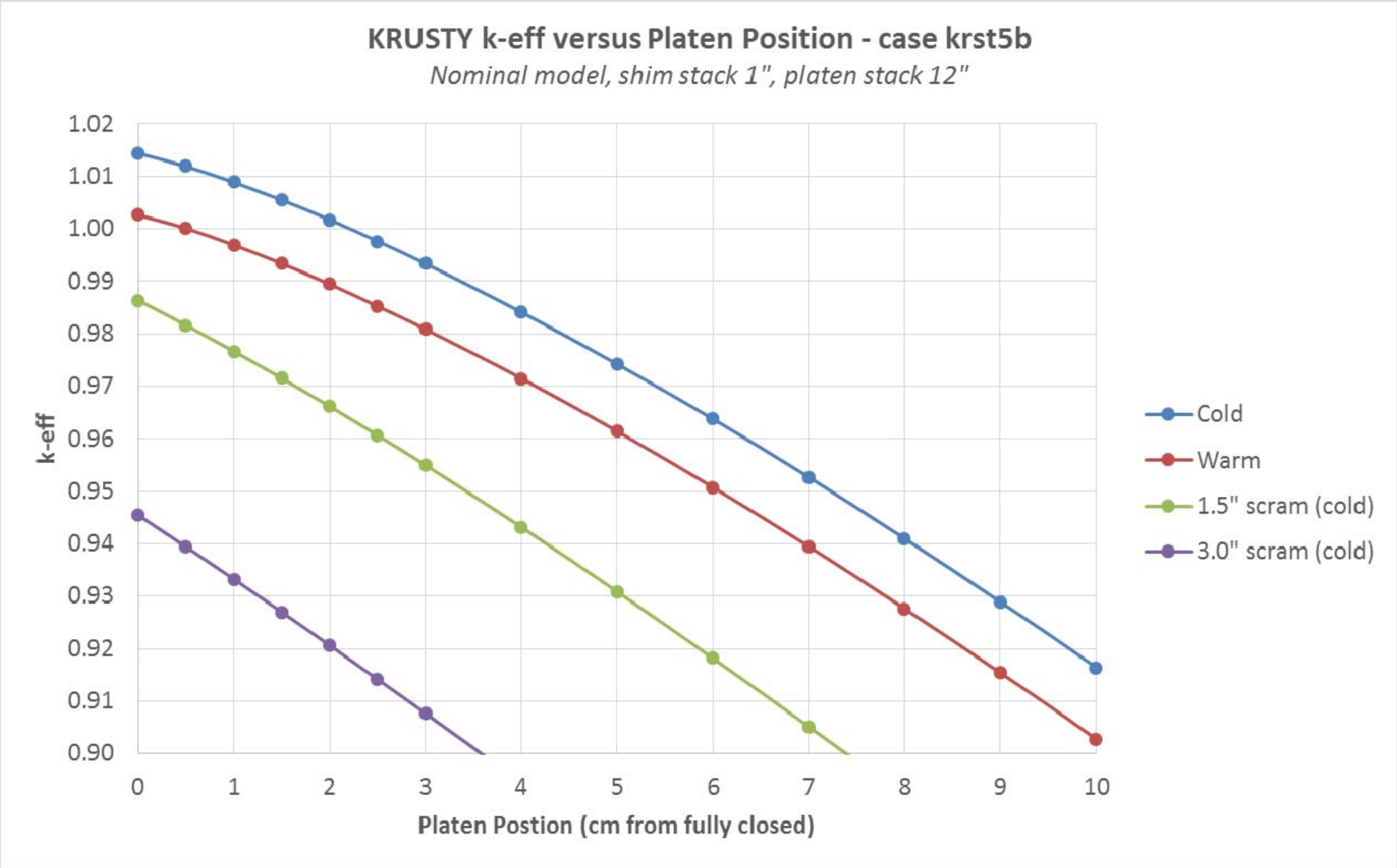
The final “full-power” run uses a higher starting/ending platen position because this provides post-test shielding to room, and will allow personnel to reenter and perform work in the room sooner.

Keff versus platen position (nominal model)



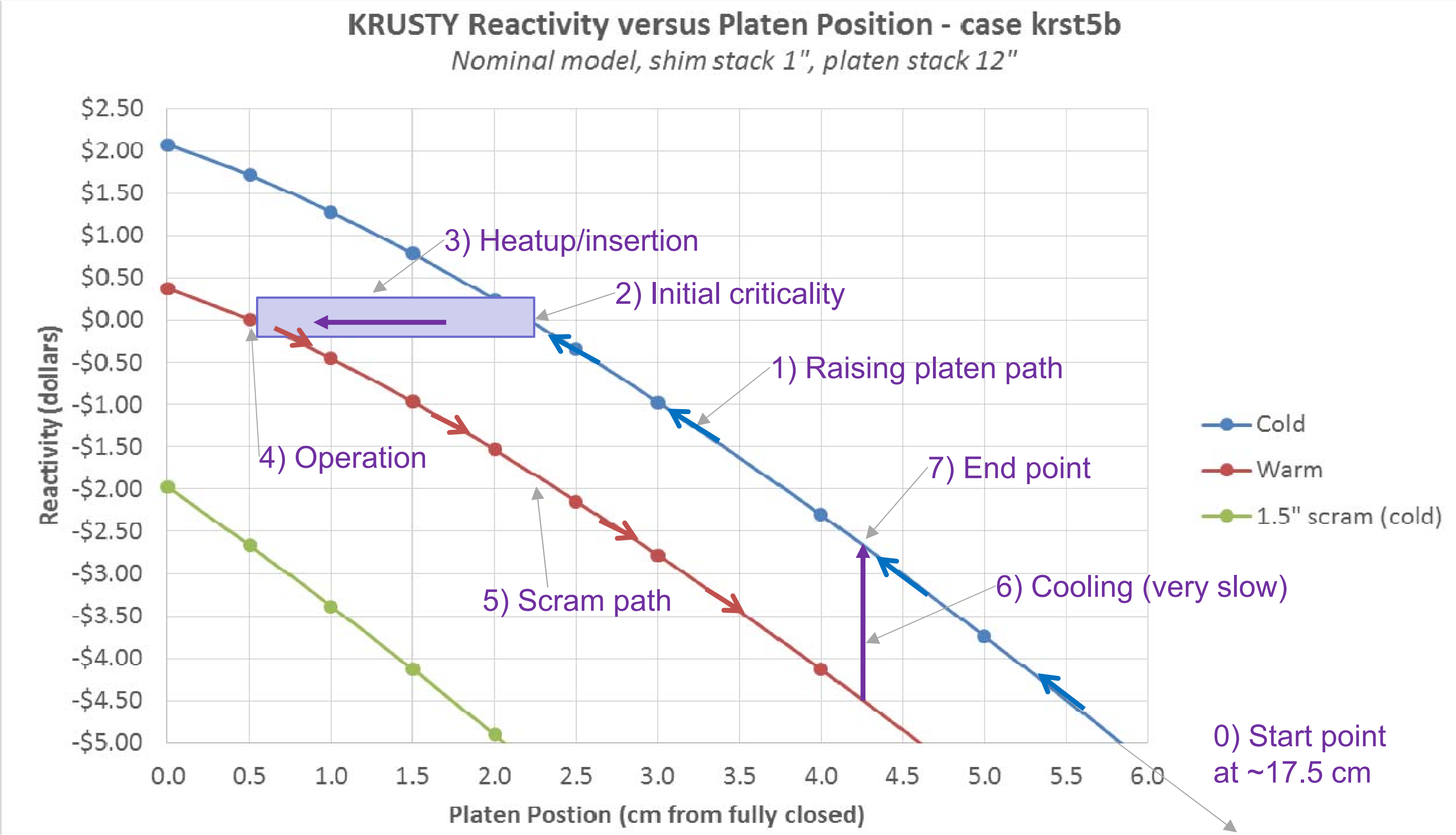
The warm is at nominal full temperature and power. This case is loaded such that it has 50 cents of excess reactivity with platen fully closed.

k-eff of nominal model



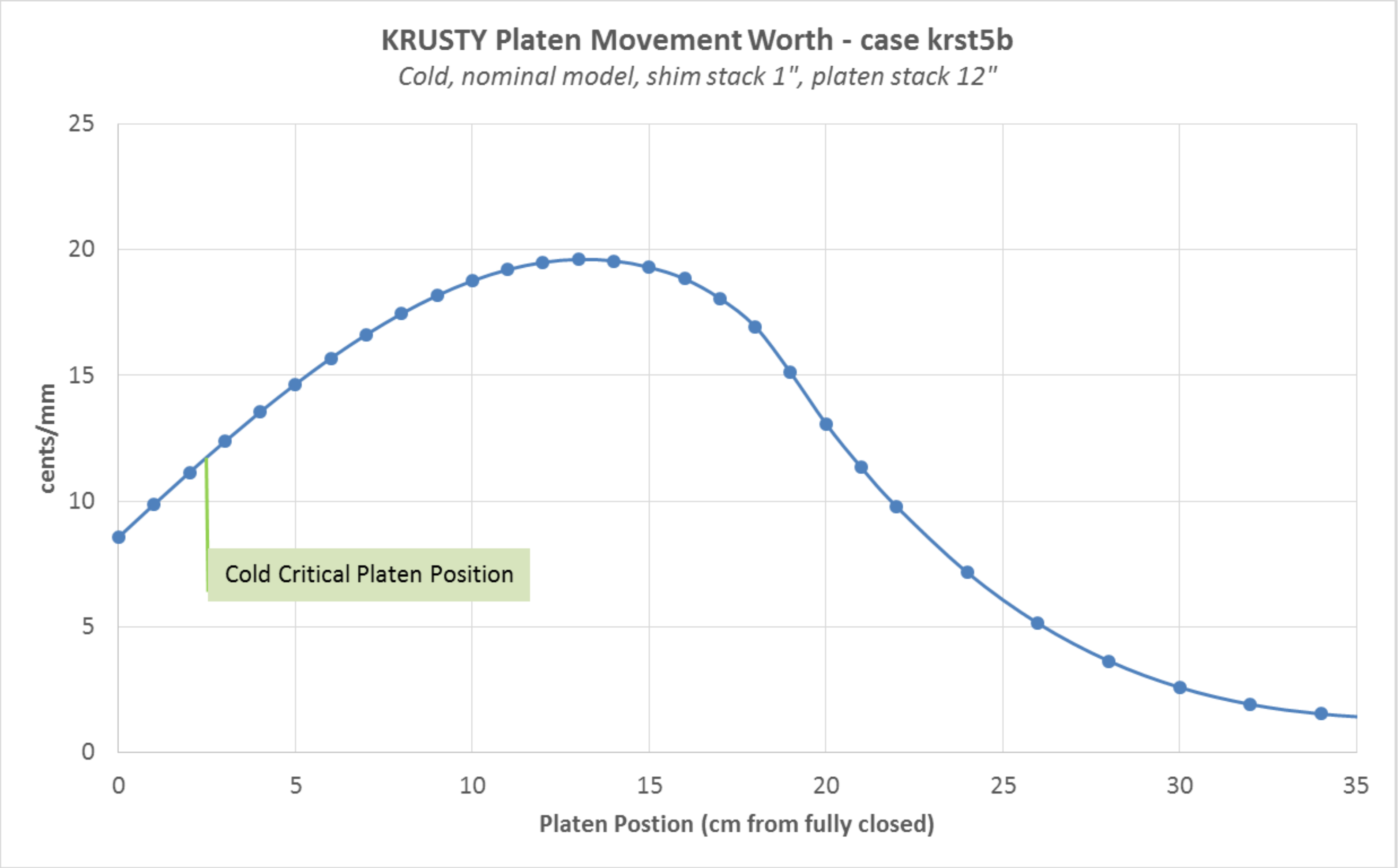
This case assumes 50 cents of excess reactivity loaded for thermal feedback margin. The cold reactor would go critical at a platen position of ~2.2cm, and as the reactor heats up the platen would slowly be raised to ~0.5cm (over 10s of minutes) to arrive at the steady state warm operating condition. The 1.5" scram is the safety requirement (must be <$1 subcritical).

Nominal startup/operation, followed by 1.5” scram



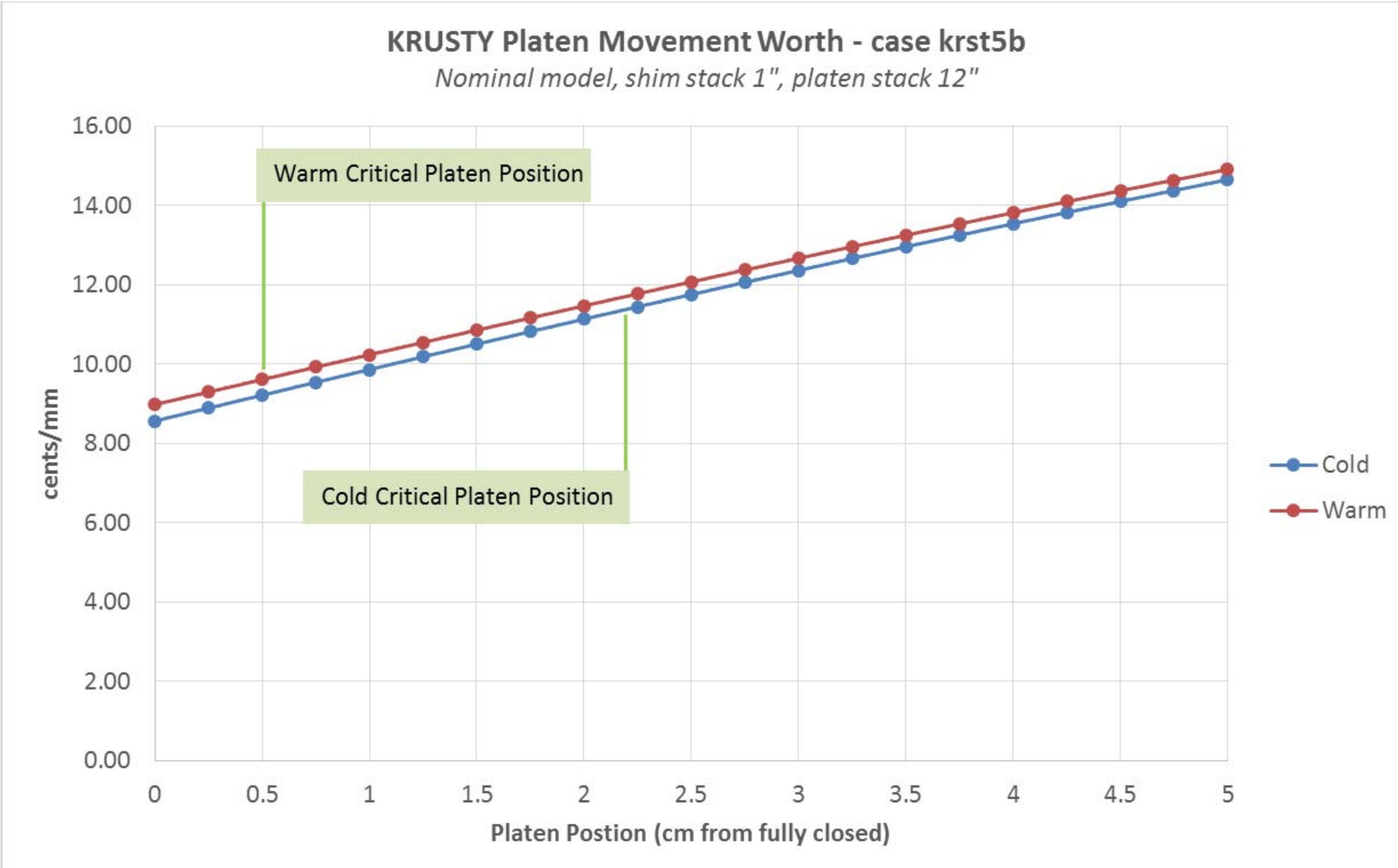
In the purple heatup/insertion zone, the operator semi-continuously (over 10s of minutes) adds small amounts of reactivity as KRUSTY warms up, to keep the system near critical (thus at constant power) until full temperature is reached. This case has $0.40 of excess reactivity margin (on top of the $1.70 defect), thus warm critical is at 0.5 cm withdrawn. Arrows then indicate a 1.5” scram, so platen falls to 4.31 cm and then KRUSTY cools down to ~$2.70 subcritical (note: even if the operator inserts too much reactivity, scram still brings KRUSTY to $2.00 cold subcritical. Normally the platen would be withdrawn to the -17.5 cm starting/stow point.

Worth of Platen Movement



Center of core is ~12.5 cm from fully closed, which unsurprisingly is the highest worth region. KRUSTY has a positive feature in that worth of platen movement gets smaller as criticality is approached and more so as additional reactivity is added.

Worth of Platen Movement near Critical



Movement when warm is worth more because 1) more leakage from fuel so reflector worth more and 2) warm fuel expands axially upward, so the radref “front” is slightly closer to the center of fuel.

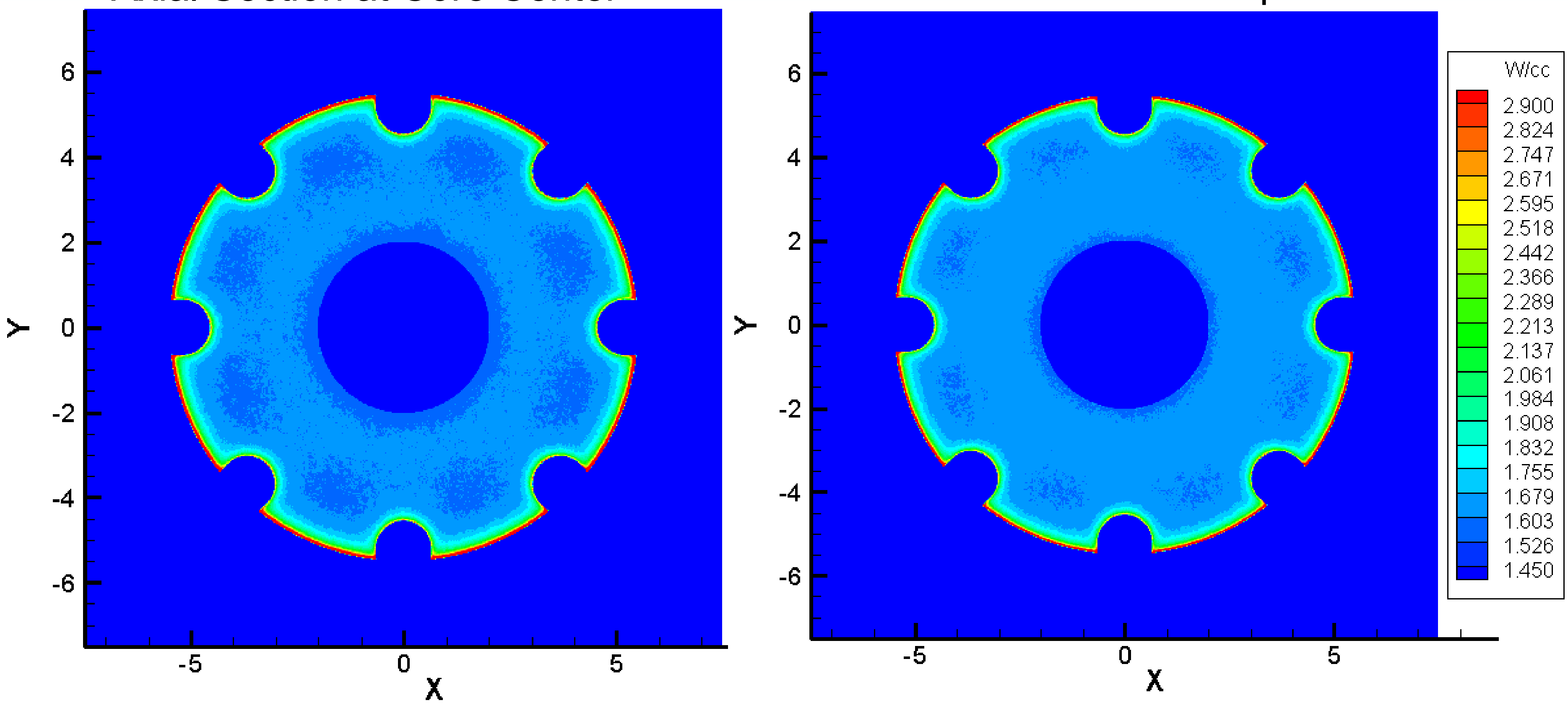
Comet Platen Insertion Rate

- Comet diagnostics are in inches
  - KRUSTY worth is ~10 cents per mm = 0.25 cents per mil (0.001”)
  - Note: the insertion rate programmed into Comet is THE rate; control is binary, on or off, so this is not just the max speed, it is the only speed.
- Zeus experiment used a guideline of <5 cents/second
  - Although the actual rates that were implemented resulted in much less than 5 cents/sec.
- Propose KRUSTY having ~0.5 cents/sec rate near warm critical.
  - This would set rate at 0.002”/s
  - This is the same as Zeus as gap is closing, but might like to use this all the way from ~0.5” to closed).
  - This would mean that a 4 second push would add ~2 cents, which would be a good rate once we’re getting pretty hot. Maybe use .004 in/s from .5” to .75” (which should be shortly after cold critical, and .008 in/s from .75” to 1” so you’d have enough speed to find a good slope (e.g. 20 cents) for the free run (.008”/s would be ~2 cents/s).
- Transients are shown further down in presentation look at heating versus insertion speed.
  - 0.400 in/s up to 5” of closure
  - 0.200 in/s from 5” to 4” of closure
  - 0.100 in/s from 4” to 3” of closure
  - 0.050 in/s from 3” to 2” of closure
  - 0.032 in/s from 2” to 1.5” of closure
  - 0.016 in/s from 1.5” to 1” of closure
  - 0.008 in/s from 1” to 0.75” of closure
  - 0.004 in/s from 0.75” to 0.5” of closure
  - 0.002 in/s from .5” to 0.0” of closure
  - 0.001 in/s from 0.0” onward (like Zeus had it)
- The base case goes critical at ~0.8” and is at full temperature ~0.15”, and we should be able to load the machine for something similar to that after the crits. However, some cases might hit critical much sooner that 1”, depending on the configuration, especially the early crits without clamps/HPs. Thus I think it makes sense to slow down quite a bit when you’re within a few inches.

Radial Core Power Deposition

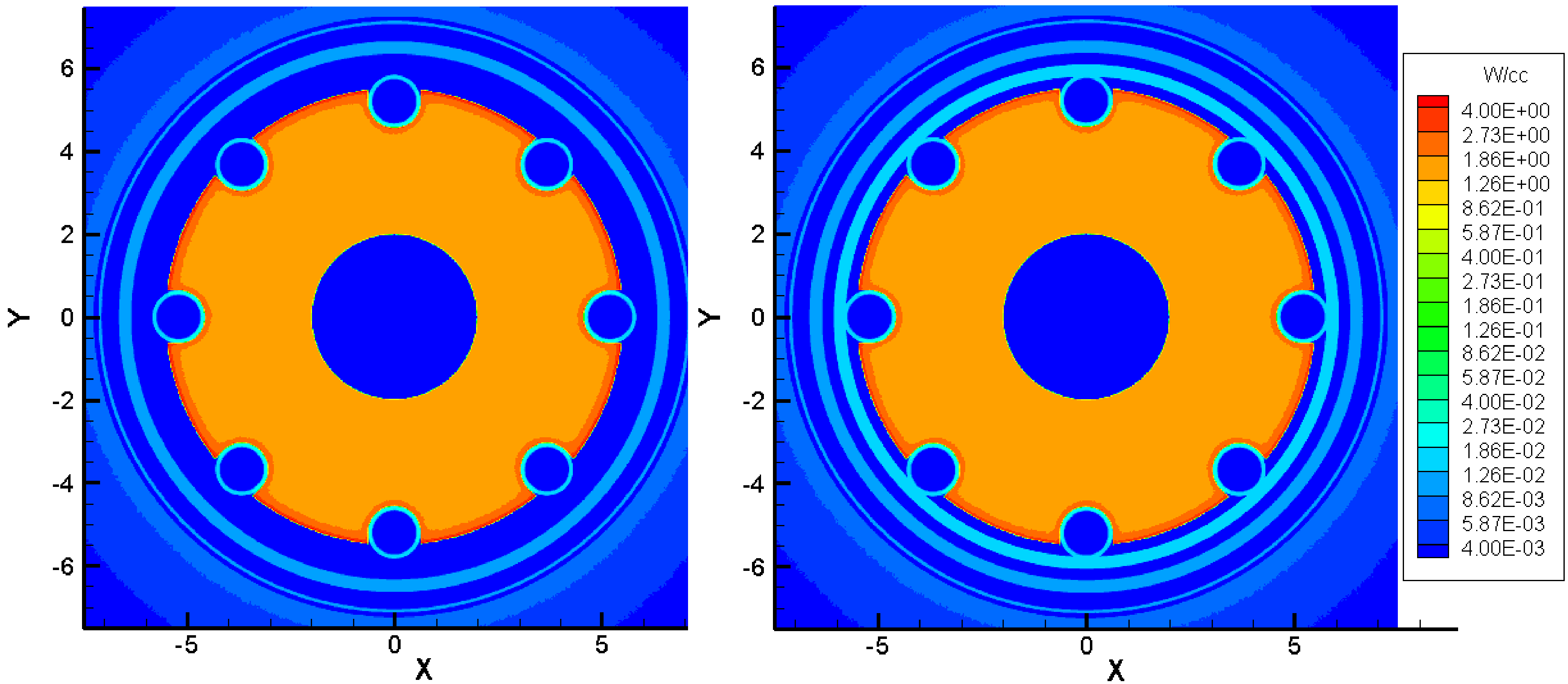
Axial Section at Core Center

Axial Section at 3rd Clamp Elevation



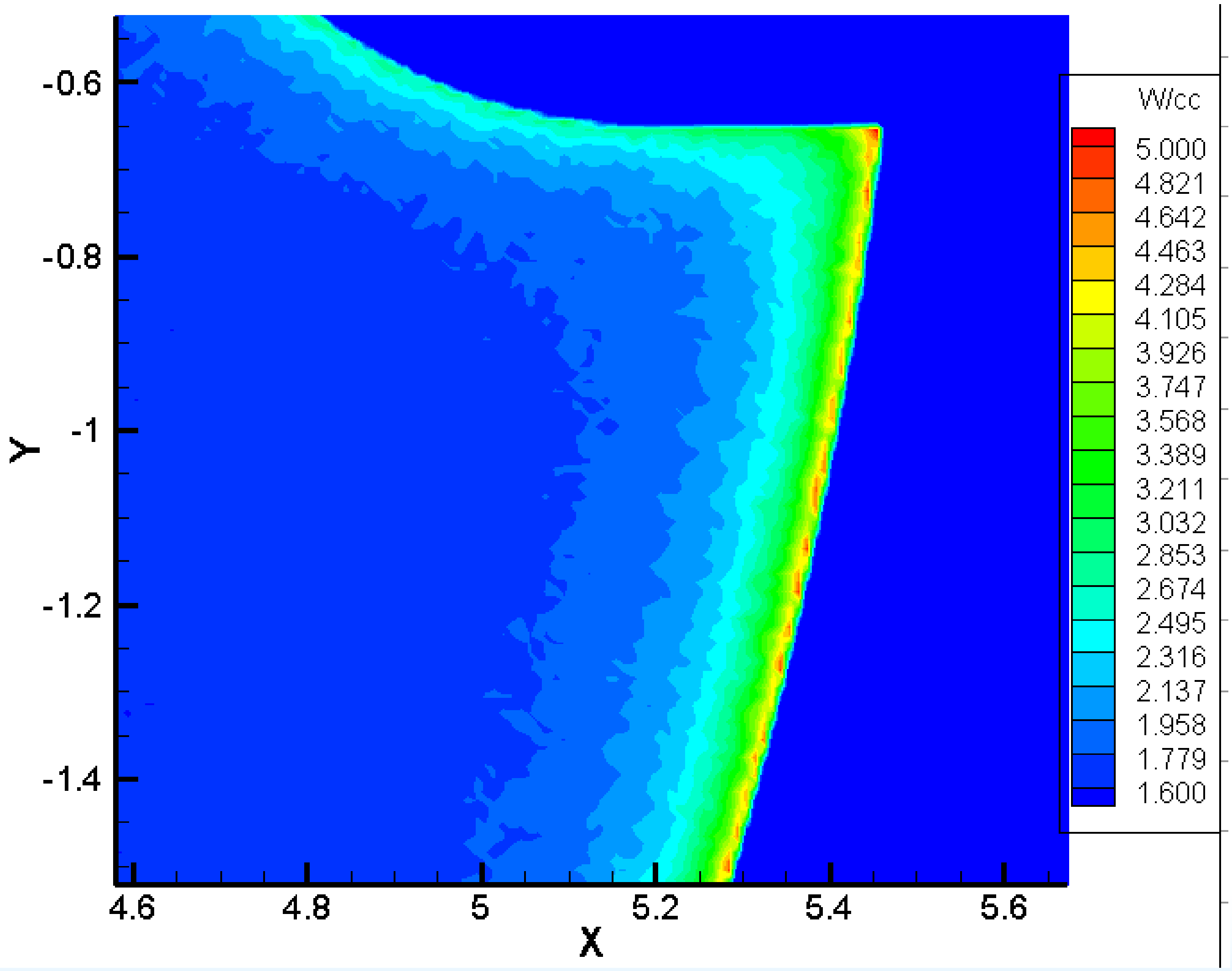
Good news is that power pretty flat, and slightly tilted outward, which reduces delta-T in the nuclear test. Bad news is that it is significantly different than resistant heated, which puts 100% on the inside (which is more conservative than we'd like). The core center section is not surrounded by a core clamp, thus has slightly more relative edge peaking. The 3rd clamp is just below core center, which actually has a slightly higher total power due to the axial peaking caused by the radref position/loading. The edge peaking discussed more in later slides.

Radial Core Power Deposition



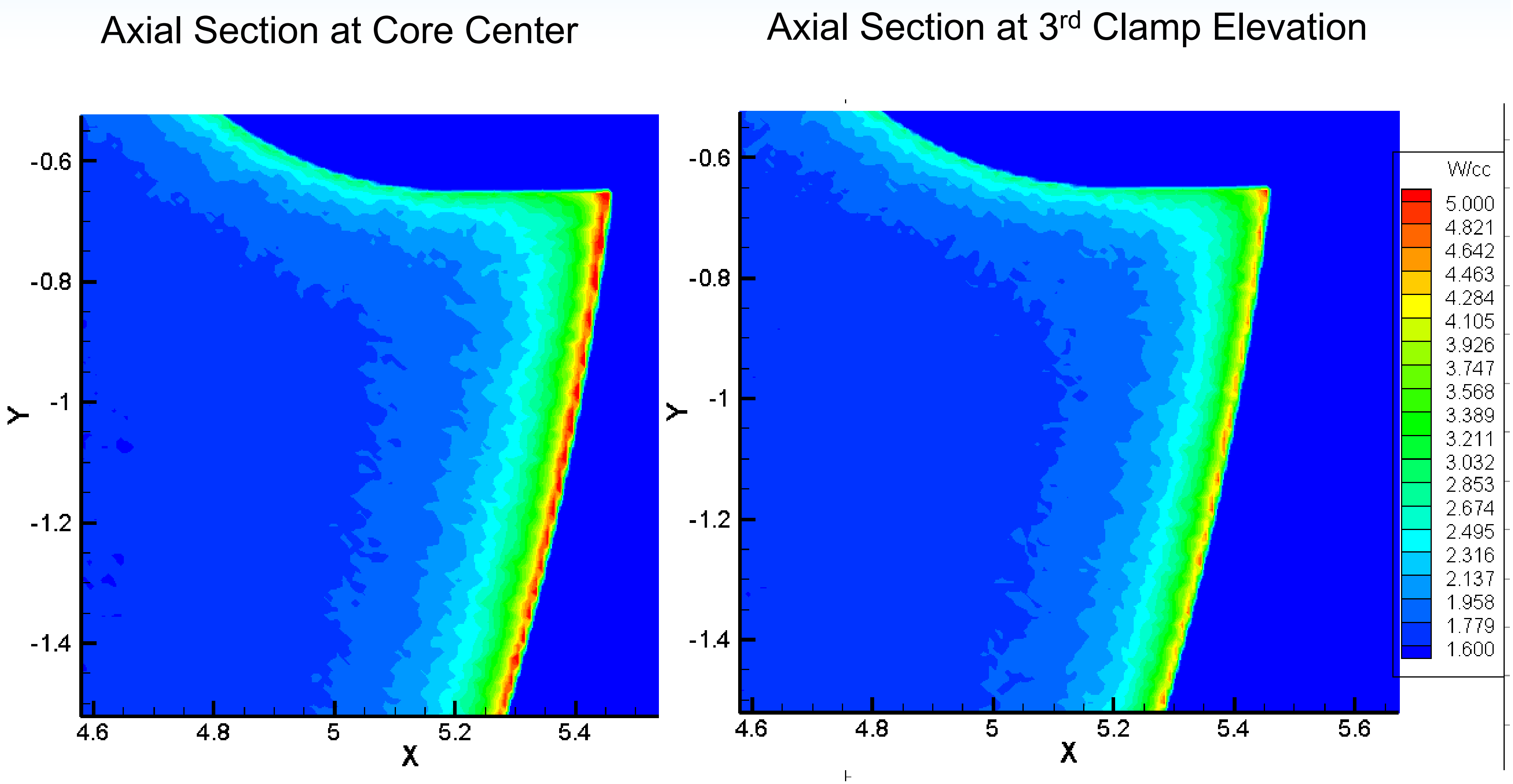
On a log scale, the power deposition in the HPs, clamp, vessel, radref sleeve, and radref BeO can be seen. The clamp has remarkably little influence on this picture, even though it does influence neutronics a fair amount (clamps drop keff by about $1). This is mostly in the edge effect.

Close up of edge peaking



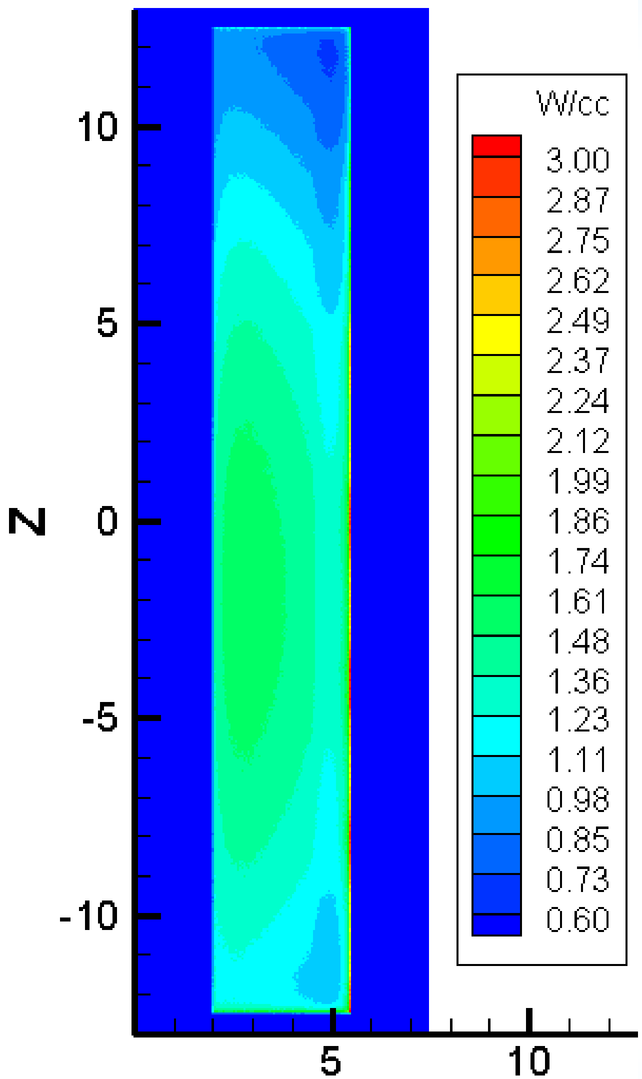
This shows the magnitude of the edge peaking, which is significant in magnitude (up to factor of 3) but is not an issue for KRUSTY (because power densities and burnups are so low). Higher power concepts are designed with much thinner reflectors, and have higher internal PDs, both which reduce this effect.

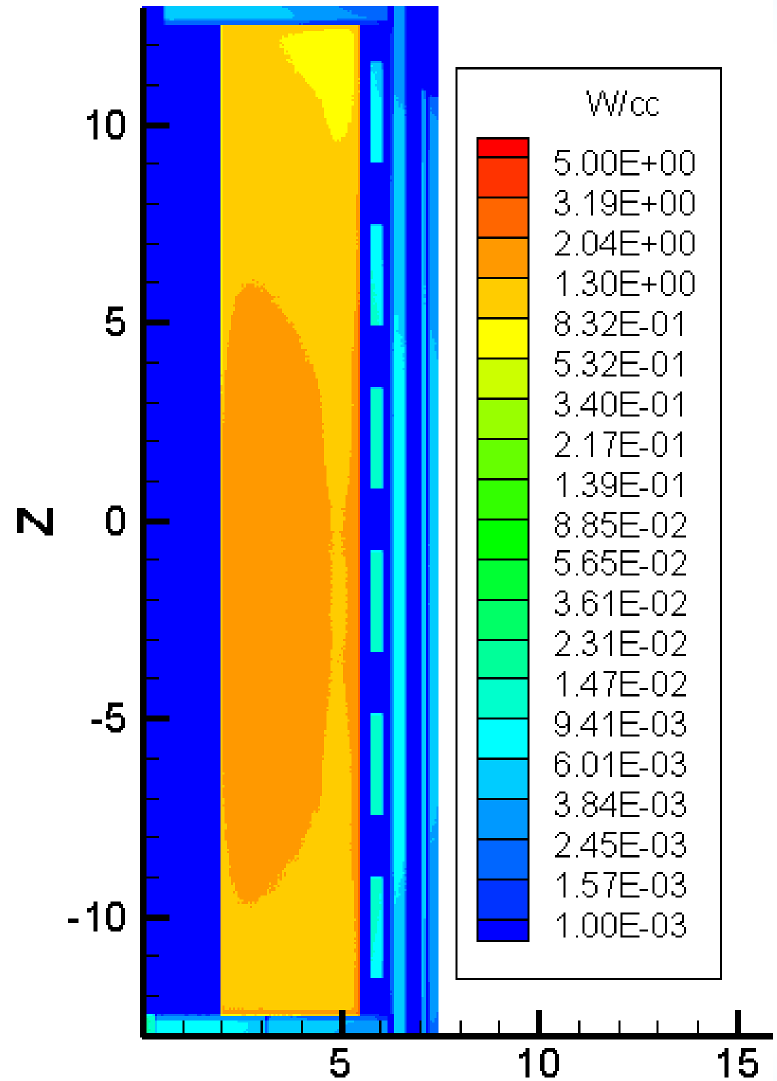
Core Clamp Effect of Edge Peaking



The peaking is higher in the region where there is not a core clamp (because the clamp absorbs lower energy neutrons, largely due to the tungsten in the Haynes-230). The grid size was set at 0.01 cm which is smaller than the mean free path of a thermal neutron in U235 of 0.03 cm, so it could be expected to see about a 25% drop over .1mm (which is about what is shown)

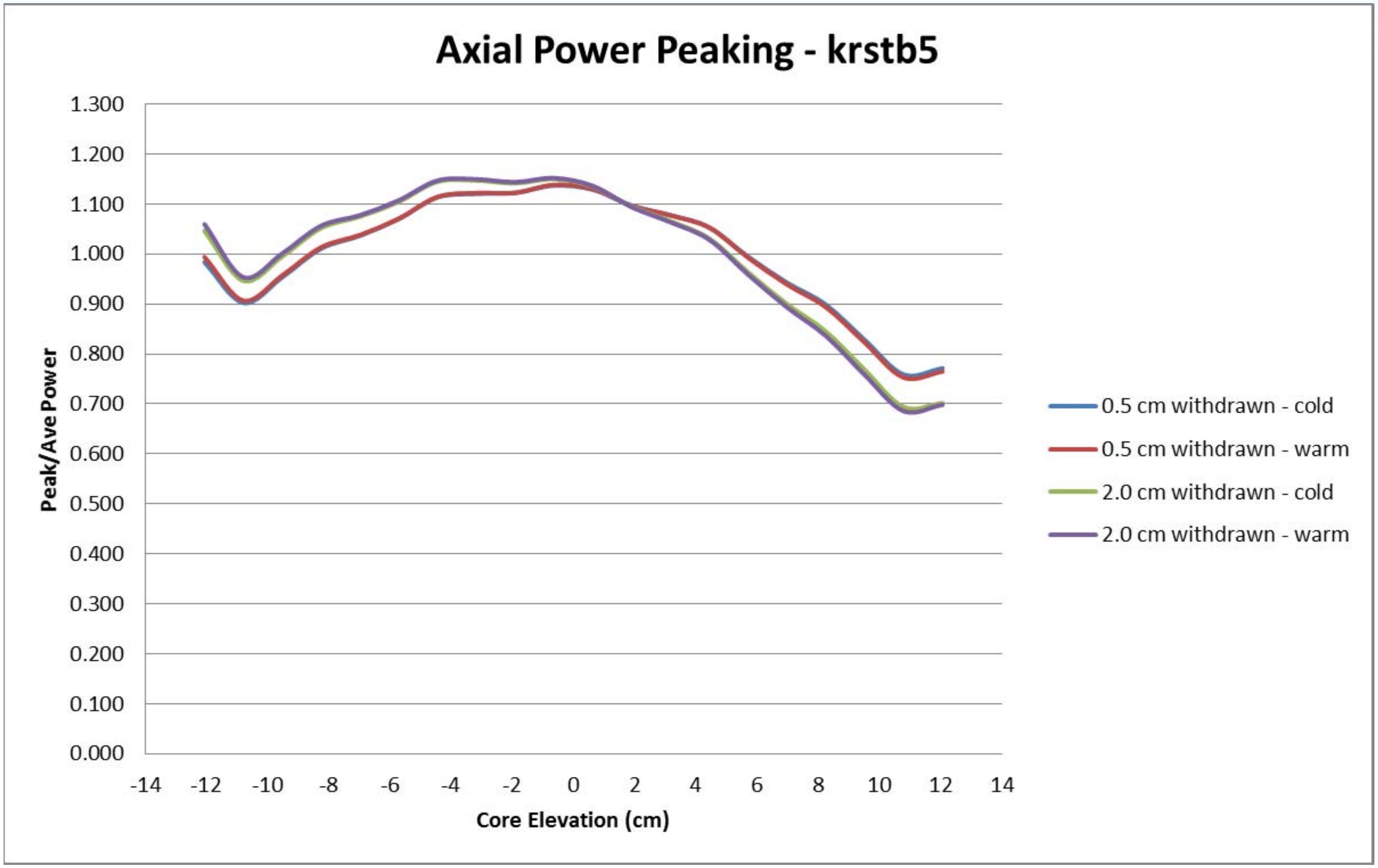
Axial Power Deposition
krst5b, cold +20cents





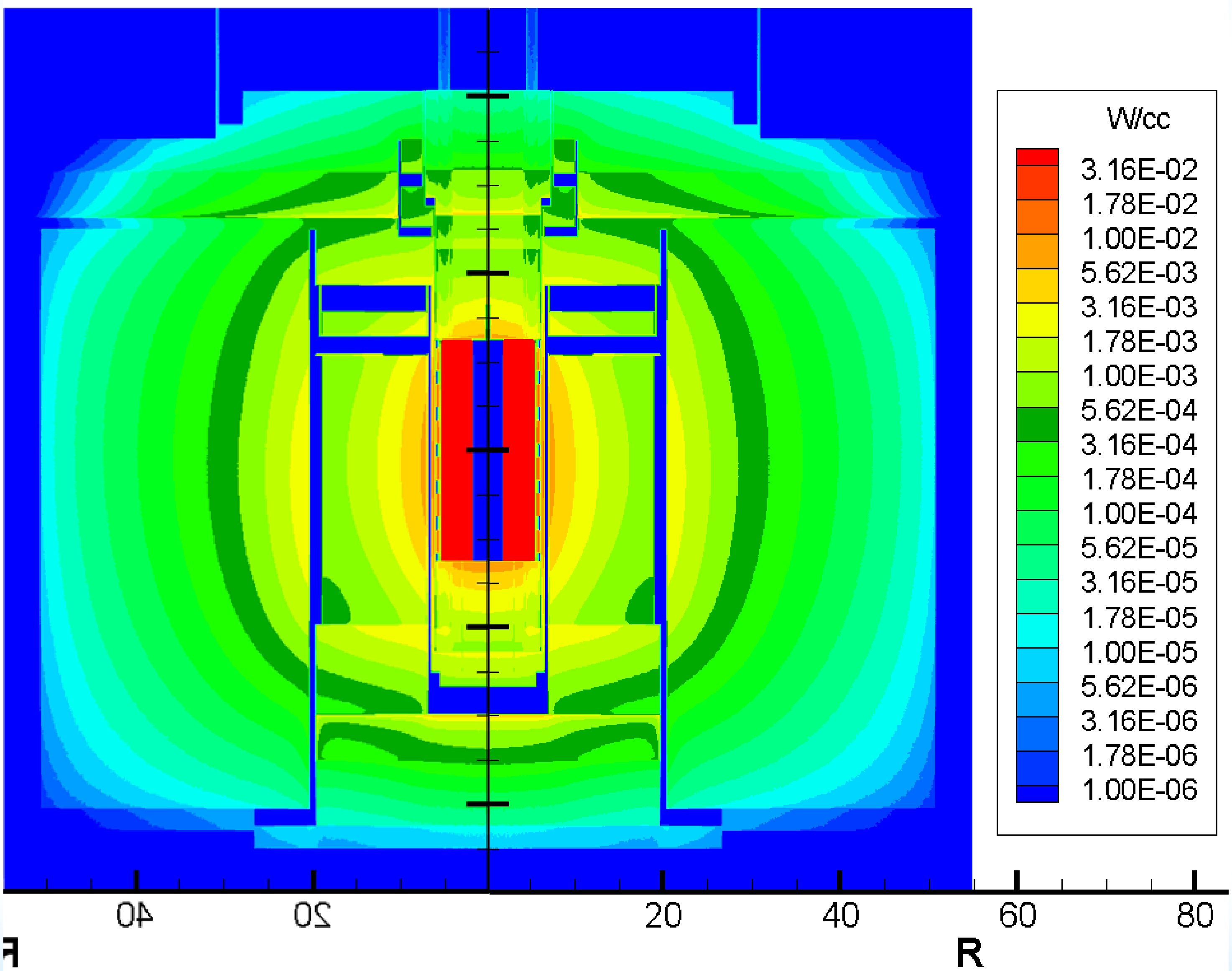
This is a r-z plot over the 25 degree azimuth in between the heat pipes. Power is skewed downward because the platen is ~2 cm withdrawn in this scenario, plus the shim stack is only partly loaded (2.54 cm). At operating temperature power deposition will be more centered (when gap closes to 0.5 cm). The peaking between the core clamps is visible, but not very strong.

Axial Power Peaking



This level of axial peaking is small compared to most reactors, despite the fact that we have an extremely large L/D. In general 10% peaking should add 10% to all temperature gradients up through the HP vapor, with a small reduction due to axial conduction through the fuel. The other consideration is how the heat pipe performs with this non-uniform heat flux, which should be no problem. Cold and warm are included simply to show there is no appreciable different. The most interesting aspect of this curve is that the effect of the core clamps is distinguishable – 5 relative peaks occur at the location between the clamps. However, the “peaks” are ~1% of power, so the net impact is minor. Finally, the chart confirms that the more closed platen position results in less peaking, but not by a great amount either.

System-wide Power Deposition



So much cool stuff going on that I added the reverse image!

Total Power by Component – krst5b

	Fraction	Watts (3kW)
heat pipes	0.00060	1.79
safety rod	0.00000	0.00
fuel	0.93872	2816.15
clamps	0.00107	3.20
multifoil	0.00025	0.74
radial vessel	0.00119	3.57
radref sleeve	0.00030	0.90
radref	0.01594	47.81
radial shield	0.02878	86.33
upper in ves SS plug	0.00009	0.27
upper in ves B4C	0.00033	0.99
upper in ves shield	0.00021	0.62
upper axref	0.00060	1.81
lower axref	0.00099	2.98
lower SS/ves	0.00019	0.57
uppermost external SS	0.00046	1.38
upper external B4C shield	0.00246	7.39
upper external SS shield	0.00035	1.06
upper wagon wheel	0.00237	7.11
support wagon wheel	0.00342	10.27
lower B4C shield	0.00144	4.32
lower SS shield	0.00023	0.69
platen	0.00001	0.04

This is used as input to FRINK, which additionally adds radial and axial profiles within the regions.

Note than krst5b does not have central B4C.

Decay Power Removal

- The nominal power density of 1.6 W/cc (@3 kW) gives the fuel an adiabatic heat up rate of 0.7 K/s.
  - Therefore there is a lot of time/inertia before high temperature is potentially reached
  - This rate is slightly higher at room temp (lower Cp) and lower at high temp (higher Cp)
    - Note: the first run of DUFF had a core heat up of almost 2 C/s for the first 2 minutes; inferring that power was about 10 kWt at that time.
- After shutdown, assuming an average of 1% power over several hours, the core would heat up only ~15 K per hour (assuming it was perfectly insulated).
  - The core is well, but not perfectly insulated, and should easily reject ~30 W to keep it from heating up too much
    - And rejection will increase if temperature does go up.
  - Also, the decay power is much lower than traditional percentages because of such short operation time.
- FRINK calculations (later in presentation) show no worries about decay power removal.
  - For 28 hour operation, and likely even if KRUSTY operated for weeks/years.

Model Bias – Over/Under Prediction

- There are numerous reasons that reactivity of the actual system could be over/under predicted.
  - Model inaccuracies
    - Cross sections
    - MCNP modeling techniques (not expected to be issue)
  - Physical discrepancies
    - Fuel density, enrichment, Mo fraction, impurities
    - Haynes 230, BeO, SS316, B4C densities, composition and impurities
    - Dimension and tolerances of parts
    - Spacing and alignment of assembled parts
    - Na level in heat pipes
    - Tolerances of Comet.
  - Environment
    - Ambient temperature (~0.2 cents/C)
    - Heat removal from components
- Calculations are performed to anticipate the difference between the calculated and measured reactivity (model bias)
  - Grossly underpredicted (-$2) – highly negative model bias
  - Underpredicted (-$1) – negative model bias
  - Nailed it – no model bias
  - Overpredicted (+$1) – positive model bias
  - Grossly overpredicted (+$2) – highly positive model bias

Excess reactivity for KRUSTY

- There are 2 reasons why excess reactivity is needed
  - 1) Excess to overcome the operating reactivity defect
    - The operating reactivity defect is the reactivity loss moving from the cold zero-power state to the nominal operating temperature/power.
    - The operating defect is quantified in 3 separate bins
      - 1a) Temperature defect – reactivity loss due to components rising to "full" temperature
      - 1b) Power defect – reactivity loss associated with the system operating at full power
      - 1c) Drift defect – the reactivity change with long-term full-power operation
  - 2) Excess to provide margin for model bias
    - The model bias is the difference between the calculations and reality, for reasons given on the previous slide or possible unknowns.
    - The model bias is quantified in 2 separate bins
      - 2a) Cold bias – the difference between the model and the zero-power criticals
      - 2b) Warm bias – the difference between the modeled operating defect and the experimental operating defect.

Excess reactivity – Current Values

- 1) Operating reactivity defect – currently calculated at $1.70
  - 1a) Temperature defect – currently calculated as $1.63
    - The main components of temperature defect is fuel expansion,
    - Nominal temp = heat pipe vapor temp ~773 C , average fuel temp 800 C.
  - 1b) Power defect – currently calculated as $0.07
    - The power defect in KRUSTY is caused by the sodium in the heat pipes
    - At zero-power, all of the Na will be in the pool at bottom of the HP
  - 1c) Drift defect – depends on length of operation: =$0.00 at 4 hours
    - Slight continued reactivity drop after 4 hours as reflector/shield heat up slowly.
- 2) Model bias margin – current calculated margin at $1.62
  - 2b) Goal is to have warm bias margin for reactor experiment of $0.50
    - I.e., goal is to load the machine with $0.50 more reactivity than we think we need to cover the operating defect – i.e. we'd load $2.20 ($1.70 + $0.50).
  - 2a) So, we hope that the cold bias margin is therefore less than $1.12
    - Note the cold bias will be well quantified by the zero-power criticals (ZPCs).
      - If the cold bias is shown by the ZPCs to be >$1.12, then we would not have the ability to load full $0.50 margin that we'd like, and the cold bias shown to be >$1.62, then we couldn't reach full temperature even if our defect calculations were correct.

Summary of excess reactivity

- Bottom line - the current model shows a cold, fully-loaded (12" BeO) system at keff=1.0229 ($3.32 excess).
  - Ideally, we would like to load on the machine with 50 cents over the predicted operating defect, $0.50 is based on the following factors.
    - We prefer a larger margin to maximize the probability of achieving full temperature.
      - 50 cents will allow for reactivity feedback to be 28% higher than predicted – this should be enough because we will also have data in the lower temperature range to reduce uncertainty.
    - We prefer a smaller margin so that the operating "air gap" (gap between platen BeO and the shim pan) is small (better shielding and power profile)
    - We also prefer smaller margin in the ALARA sense in terms of insertion accidents.
    - Initially, we had planned on having closer to a $1 warm margin, but the warm criticals (15,30,60) will give us a better prediction of the defect.
  - The current model predicts $1.70 operating defect, and we might expect the results of the warm crits to change our prediction by +/- 30 cents, thus we'd want to load between $1.90 and $2.50

Summary of excess reactivity

- Unfortunately, our core pieces are discrete, and a ¼" BeO ring is worth between 30 and 60 cents (depending on location, as shown on an earlier slide "Worth of ¼" BeO rings").
    - E.g, say we'd want to load \$2.20, but if… with .25" in the shim stack we are only at \$2.10, then we'd want to add another .25" of BeO making the loading \$2.65
    - We do have some flexibility to use SS316 or Al pieces, or only parts of the BeO ring, but these options are limited and are not ideal from an experimental perspective.
    - We are also exploring the feasibility/cost of a 1/8" BeO inner ring.

- So in-the-end, when the time comes, our loading will be based.
  - \$1.70 (current model operating defect)
  - +/- \$0.30 (change in predicted defect based on data from warm crits)
  - + \$0.50 (desired margin)
  - +\$0.00 to +\$0.50 based on discrete increment capability.
- This means <u>our loading could range from \$1.90 to \$3.00</u>, depending on how these factors line up.
  - Note, there will be very little uncertainty in the amount of reactivity we physically load, based on the results of the zero-power criticals.
    - The uncertainty lies in how much of this reactivity we actually need to heat up.

KRUSTY: 3 Types Of Nuclear Operations.

- Approach to Critical
  - Measures the neutron multiplication of a source
    - This testing starts with a configuration that is accepted to be significantly subcritical, and the steps towards criticality.
      - For KRUSTY, this is done by adding BeO to reflector the stack.
    - For KRUSTY, the ability/inability to put source and detector in “high worth” areas may require fairly high k-eff (>.98) to obtain statistically significant results.
- Zero Power Critical (ZPC)
  - Measures the k-eff of a delayed-supercritical system from the slope of power increase
    - These tests are performed at powers so low that there is negligible radioactive buildup and negligible temperature change caused by the fissions.
- Reactor Experiment (REX)
  - Fission power heats up the system, which in turn provides neutronic feedback that subsequently effects fission power.
    - Excess reactivity is required in the system to sustain criticality as the reactor heats up (which causes drop in reactivity).

We considered Electrically-Heated Criticals

- Advantages
  - Reduce the uncertainty in temperature defect (i.e. reactivity required to heat reactor from room temperature (~20 C) to operating temperature (~800 C).
    - Heating will not be prototypic, which diminishes value
    - What configuration? - with or without HPs attached, need the reactivity of shield, need vacuum
  - Gain cleaner data to aid in prediction of temperature feedback effects for other systems.
    - This is likely a small benefit, because feedback is dominated by expansion, and KRUSTY may be unique in 1) how it expands and 2) the worth of expansion (e.g. the specifics of how it is reflected, placement of B4C etc.).
    - It will be very hard to separate out the small effect of cross sections, which is much easier done in a spherical system with uniform reflection (e.g. Flattop).
- Disadvantages
  - Extremely difficult to implement – i.e. the ability to heat fuel/components while maintaining enough reactivity to measure worth.
    - From the start, we considered and hoped perform a non-nuclear test of the system on Comet before nuclear-power, but we were not able to come up with a way to make it “work” without major changes to the test article and apparatus.
    - Hard to getting a heater into KRUSTY without removing needed neutronic worth provided by the axial reflector and shielding.
    - Hard to feed electrical leads into system, and issues to accommodate movement and ensure un-encumbered platen movement were also difficult.
  - Thermal cycling may be a major issue with the Kilopower concepts, such that reactor will not perform as well/expected with increasing thermal cycles, but most notably the first cycle
    - It is very important to know if there is significant degradation and if so, how much, because a space reactor could be designed for no thermal cycles if needed.
    - Without HPs working it’s hard to cool down fuel thermally.
  - Asset and safety risks would be added by heating the fuel on Comet.
    - Heater contact with fuel causing fuel melting
    - Voltage arc between heater and fuel causes melting
    - The use of additional high-power, high-voltage components add incremental risks with experiment and operations.

Decided to use Nuclear-Heated "Criticals"

- The inability to practically perform heat criticals that produce useful information for KRUSTY led to the decision to perform nuclear-heated criticals.
- Load the system with relatively small amounts of reactivity (<60 cents) and perform short tests.
  - See how close feedback is to predicted
    - Use performance of these tests to confirm/learn how KRUSTY performs.
    - If any of these tests shed doubt on our ability to safely go to higher reactivity and temperature, then we stop/pause.
  - A relatively slow heatup to <500 C should not cause significant thermal cycle issue.
    - If any plastic deformation/slack of clamps/HPs/fuel occurs, it should be gained back and then some for the first test at 800 C.
    - Potential for fuel phase change causing an issue at <500 C should be negligible.
- Biggest potential problem with nuclear-heated crits might be having to wait for system activity to cool down until the loaded reactivity can be adjusted (as needed).
  - Calculations indicate (included later) that this wait should not be long (1 to 4 days), depending on how "ambitious" these tests are in terms of energy produced (power*time or kWh).

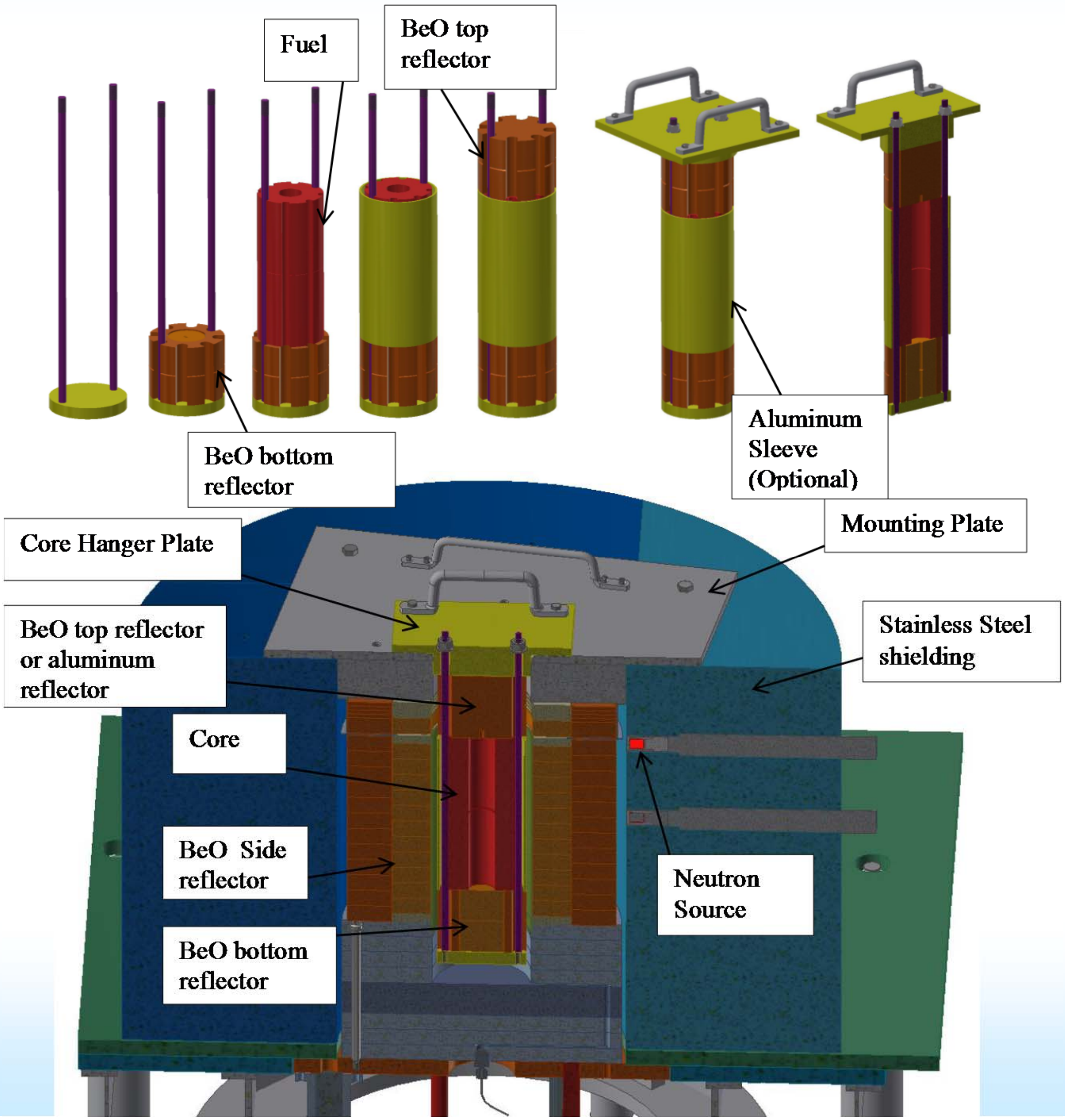
KRUSTY: Summary of Possible Experiments

- Preliminary Approach to Critical, and Zero-Power Criticals
  - Prior to KRUSTY final assembly, use fuel, reflector and other components to gain “cleaner” neutronics data.
- KRUSTY Approach to Critical
  - Start at low k-eff. Increment BeO rings to determine the stack height for the first critical.
- KRUSTY First Critical
  - Set BeO height based on “approach” and determine k-eff based on power slope
- KRUSTY Seesaw Criticals (up to 20 critical configurations, depending on time available)
  - Alternate reactivity increases (via adding BeO thickness) with reactivity decreases (via adding B4C rod thickness)
- KRUSTY Warm Criticals
  - Three separate tests which insert 15, 30 and 60 cents of reactivity, which are monitored for power, temperature and reactivity feedback
- KRUSTY Final Run
  - Start the same way as warm criticals, but continue to add reactivity until an average fuel temperature of 800 C is reached, demonstrate Stirling engine operation, system dynamics, etc.

Preliminary Crits

- Evaluate various configurations of KRUSTY components with approaches to critical (when needed) and ZPCs.
  - Goal is to try and get "clean" physics data for various materials/components,
    - Useful to the physics community at large
    - Aids in future Kilopower reactor designs.
    - Provides confidence in proceeding with KRUSTY experiment
  - Probably >90% of the physics value of KRUSTY will be gained with the first critical (no matter what the configuration).
    - I.e. a measurement of a highly-reflected BeO experiment.
      - This is probably the only area where there could be vast difference between experiment and codes/data.
    - Follow on experiments will likely be fine tuning uncertainties, but still important and if easy to perform will provide good bang for the buck.
      - Plus, there's always the "that's why they play the games" possibility that something unexpected will arise.

Preliminary crits

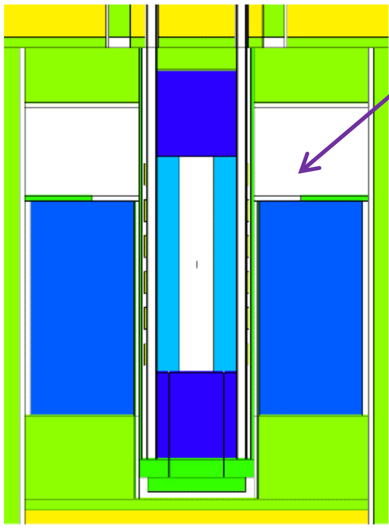


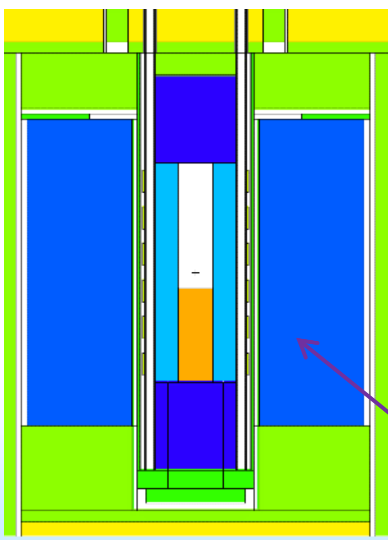
Full assembly w/o vacuum vessel, heat pipes, core clamps, and insulation

Possible “See-Saw” criticals sequence

based on old model, krst1g – prior to shim stack

This represents the full suite of proposed crits, and may be reduced for schedule reasons.





case	BeO Short-stack	B4C Rod-stack	keff	Reactivity	Reactivity Increment	BeO worth per 0.25"	B4C worth per 0.25"
	Inches	Inches		$	$	$	$
krapp1	4.00		0.96175	-$5.54			
krapp2	3.50		0.97432	-$3.72	$1.82	$0.91	
krapp3	3.00		0.98616	-$2.01	$1.72	$0.86	
krapp4	2.75		0.99164	-$1.21	$0.79	$0.79	
krapp5	2.50		0.99674	-$0.47	$0.74	$0.74	
kzpc1	2.25		1.00177	$0.26	$0.73	$0.73	
kzpc1b	2.25	0.125	1.00100	$0.14	-$0.11		-$0.22
kzpc2	2.00	0.125	1.00555	$0.80	$0.66	$0.66	
kzpc2b	2.00	0.750	1.00067	$0.10	-$0.71		-$0.28
kzpc3	1.75	0.750	1.00497	$0.72	$0.62	$0.62	
kzpc3b	1.75	1.500	1.00073	$0.11	-$0.61		-$0.20
kzpc4	1.50	1.500	1.00488	$0.71	$0.60	$0.60	
kzpc4b	1.50	2.125	1.00063	$0.09	-$0.62		-$0.25
kzpc5	1.25	2.125	1.00452	$0.66	$0.56	$0.56	
kzpcc5b	1.25	2.625	1.00072	$0.10	-$0.55		-$0.28
kzpc6	1.00	2.625	1.00441	$0.64	$0.53	$0.53	
kpzc6b	1.00	3.000	1.00128	$0.19	-$0.45		-$0.30
kzpc7	0.75	3.000	1.00452	$0.66	$0.47	$0.47	
kzpc7b	0.75	3.375	1.00123	$0.18	-$0.48		-$0.32
kzpc8	0.50	3.375	1.00420	$0.61	$0.43	$0.43	
kzpc8b	0.50	3.750	1.00085	$0.12	-$0.49		-$0.32
kzpc9	0.25	3.750	1.00343	$0.50	$0.37	$0.37	
kzpc9b	0.25	4.000	1.00102	$0.15	-$0.35		-$0.35
kzpc10	0.00	4.000	1.00345	$0.50	$0.35	$0.35	
kzpc10b	0.00	4.250	1.00080	$0.12	-$0.38		-$0.38

Standard deviation on calcs ~2 cents

Reactor Experiments (REX)

- Zero power crits will let us know how much reactivity we have on the machine.
  - To within a few cents
- The unknown will be the temperature defect; i.e. the total reactivity feedback moving from room temperature to 800 C)
  - Cross section uncertainty in not significant
    - Cross section based feedback is small, and almost all attributable to U235 and U238, which we know very well
    - Be not a big factor, because radial reflector does not heat significantly, although there is a small axial reflector cross section effect.
  - The biggest uncertainty will be how fuel expands
    - At low temperatures (<~600 C) all the experimental CTE data agrees fairly well, so we should know cte fairly well based on historical data.
    - Electrical testing will shed some light on overall expansion.
- Plan is to start with small insertions to slightly raise system temperature and measure feedback and response.
  - Each subsequent test starts identically to the first test, to ensure that nothing has failed/changed or perhaps been accidentally altered.
    - I.e. everything is proceeding as expected, so ok to keep going.

Warm Criticals

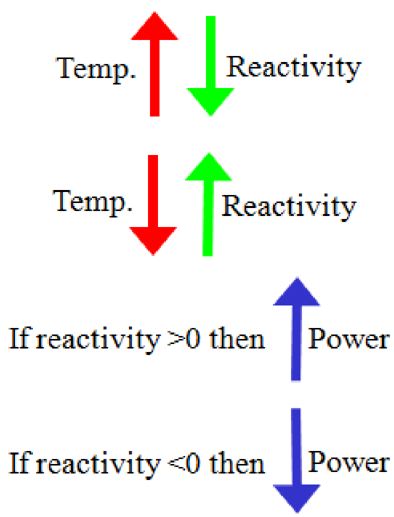
- Start with hand crank as lowest/loading position, load to closest 1/4" that predicts at least 20 cents (i.e. load between $0.20 and $0.80)
  - If possible (enough margin), would like B4C in the core for this and all of the powered runs.
    - It is more flight prototypic - the flight system design would have about 5 cm in core (for burnup and margins)
    - It also flattens the power distribution quite a bit, thus reducing core peak temperatures
    - It also would allow operation with a more-closed air gap between radref and shim stack, better shielding.
- REX1 -- 15 cent free run, let power settle at ~steady state, lower platen, cold flush
  - Model predicts max power of 3.3 kWt, peak fuel temp = 487K / 215C
  - This test is very important because allows calibration of the neutron count (log-N) with the fission power, which will be very good to know for subsequent testing and benchmarking.
    - Calibration is performed by correlating the temperature rise as a function of integral neutron count.
  - 15 cents was chosen because it provides a peak power than is gentle enough to prevent clamp/HP/fuel strain, but provides enough heating to calibrate log-N with power
    - Note, the current model is actually inserting 14 cents, but for now calling it 15 cents (for this a subsequent tests) because 15/30/60 sounds good (and by the time we get all of the final components the predictions will change a bit).
  - At least one free run is highly desirable because it eliminates uncertainty of how much reactivity was actually inserted (the established power slope allows fairly accurate calculation); therefore we can use the entire transient to better estimate how much reactivity feedback actually occurred as the temperature changed.
- REX2 – 30 cent run: start with 15 cent free, then run at about 3 kWt until a total of ~30 cents is inserted, let power settle to approx steady state, lower platen, cold flush
  - If 1/4" needed to get > 40 cents, wait 'til dose settles and add 1/4“
  - The current model predicts that the fuel temperature will be ?? At this time and settle to ??
  - If 1/4" needed to get > 60 cents, wait 'til dose settles and add 1/4"
- REX3 – 60 cent run: start with 15 cent free, then take fuel temp to 673 K (400 C, ~60 cents), let power settle to approx steady state, lower platen, cold flush

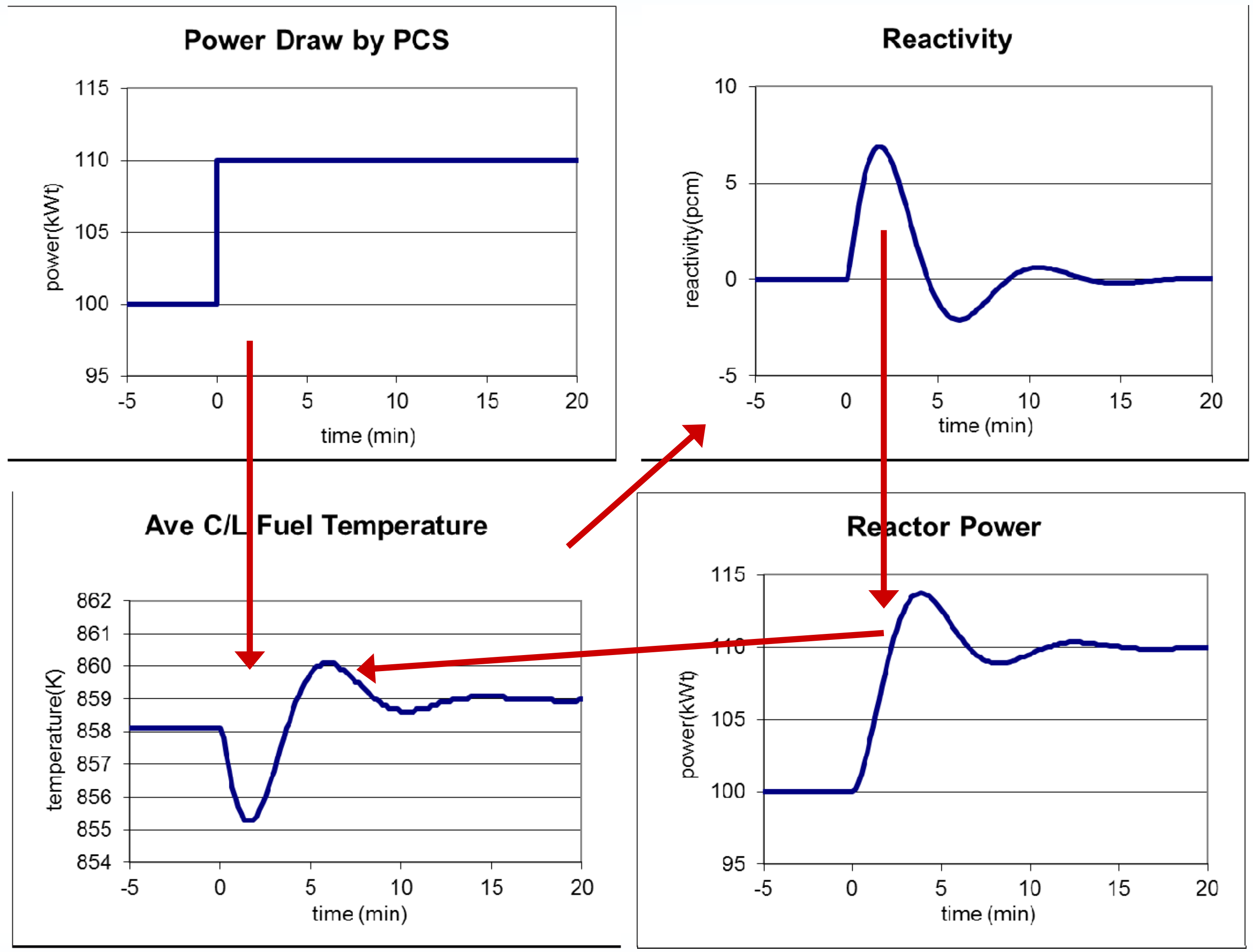
KRUSTY Final Run

- Wait until dose settles from $0.60 run (2 to 4 days).
- Load platen with closest 1/4" to give desired excess reactivity, most likely ~$2.50 (refer to excess reactivity slide))
- Hand crank platen to 7.5 cm above bottom of fuel
- REX4 -- 15 cent free, then take fuel to 1073 K (peak <1123), then… (~28 hours of operation)
  - turn on Stir+Sims when head reaches 923 K, this will occur before fuel full-temp (set Sims at same power removal as Stir), after full temp reached coast a while (~steady)
  - cut Stirling power removal by a factor of 2, ~steady,
  - increase Stirlings back to max, ~steady
  - run overnight (~2.4 kWt, or whatever power where Sims match Stirling heat removal)
  - take the Sims to max power removal (~3 kWt total), leaving Stirlings as is, ~steady, then take Sim power back to match Stirlings, ~steady
  - totally cut 1 Sim (failed HP) (don't do this for Stirling because the resulting high temp might make engine hard to restart), ~steady,
  - increase other Sims to try to get full power back, then restore all to nominal
  - totally cut power removal from Stirlings and Simulators, let coast for 2 to 4 hours.
  - scram/shut-down
- Again, the reason to start each run with a 15 cent free run (i.e. no change in reactivity input, at least until power turnaround), will give confidence that nothing has changed between runs.
  - Note that 15 cent may not be the best number, and FRINK results may change a bit once regional fuel feedback is included.

Reactor load following example
10% increase in thermal power removal

This scenario assumes an immediate 10% increase in power draw by the power conversion system. No reactor control action is simulated. No secondary feedback from the PCS is modeled.





This is a simplified example with only one feedback coefficient – bulk fuel temperature. Note that the centerline temperature settles higher than it started, because of the larger fuel temperature gradient caused by the higher power. The "actual" system response will not be this simple, but can be similar if the system design is "neutronically" simple.

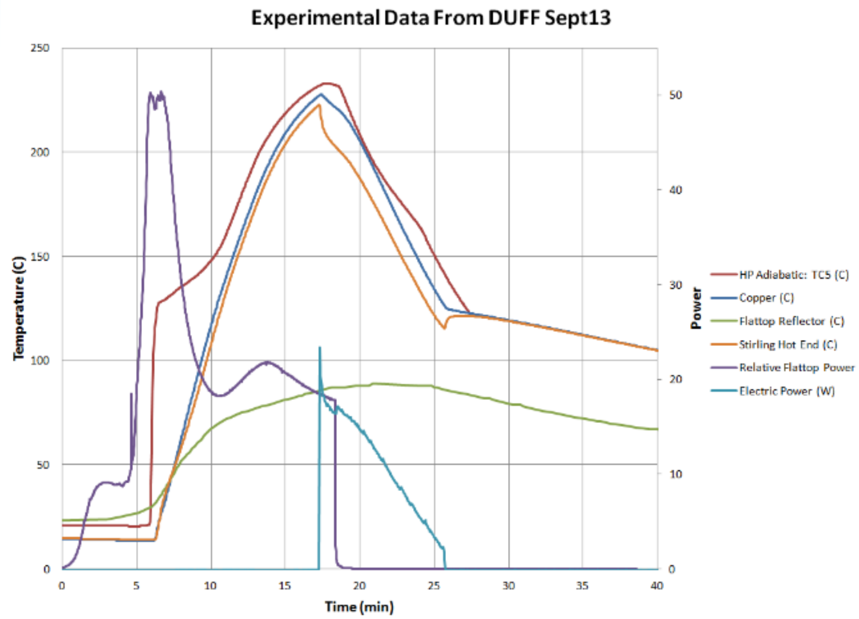
KRUSTY Final Run will follow the same procedure as DUFF runs

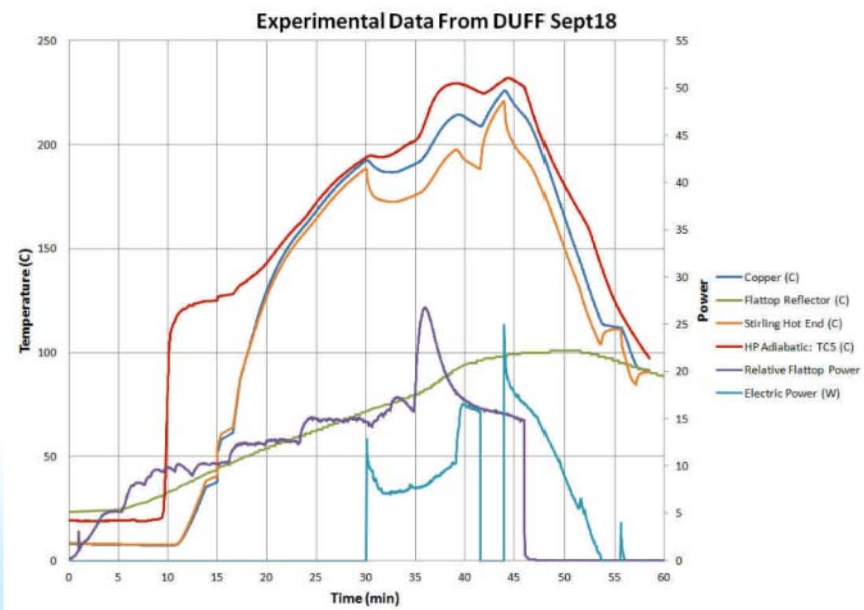
DUFF Experiments:

1. Find delayed-critical point with a “nice” reactor period (via fine tuning of reactivity by operator); nice is high enough to not take hours to get sensible heat and low enough to help avoid large power spike.
2. Let power ramp up via period and then remove reactivity to achieve a low power plateau (operator adjusts reactivity to find plateau, i.e. keff=1)
3. Insert reactivity to ramp to higher power and decrease reactivity to find newer/higher plateaus (level of decrease depends on possible reactivity feedback). Repeat as needed
4. Once thermal feedback has kicked in, then at each plateau insert small quasi-continuous reactivity insertions to keep power constant (again keff=1). DUFF power plateaus ranged from a few to 10 kWt.
5. Turn on Stirling engine once it reaches desired temperature.
6. Continue inserting reactivity until you run out of juice (excess reactivity), which for DUFF was when fuel temperature maxes out at ~300 C.
7. Remove reactivity and commence shutdown operations

KRUSTY Reactor Experiments (REX):

1. Same
2. Same, but free run may have different value
3. Same
4. Same
5. Same
6. Same, but continue insertions until ~800 C is reached.
7. Same





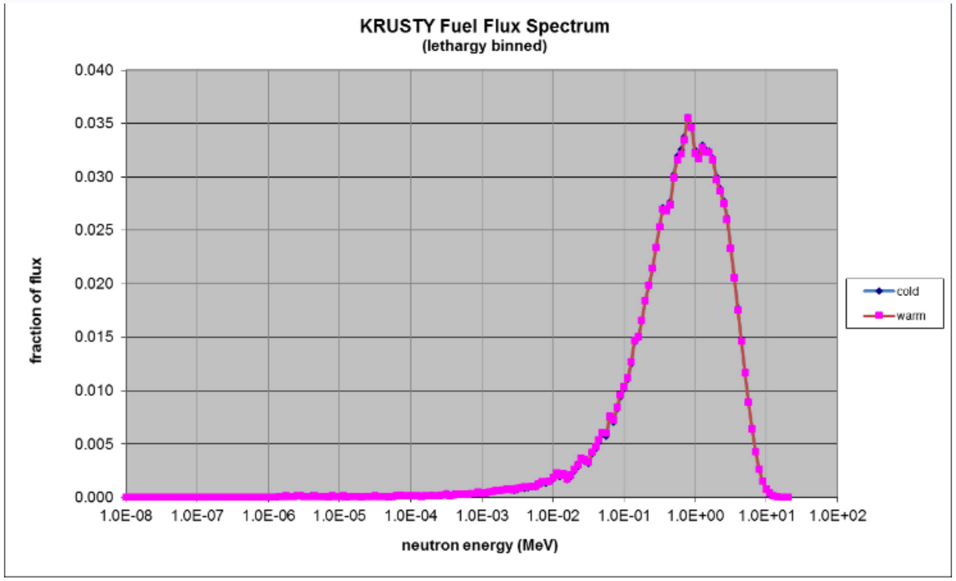
Kinetics Parameters

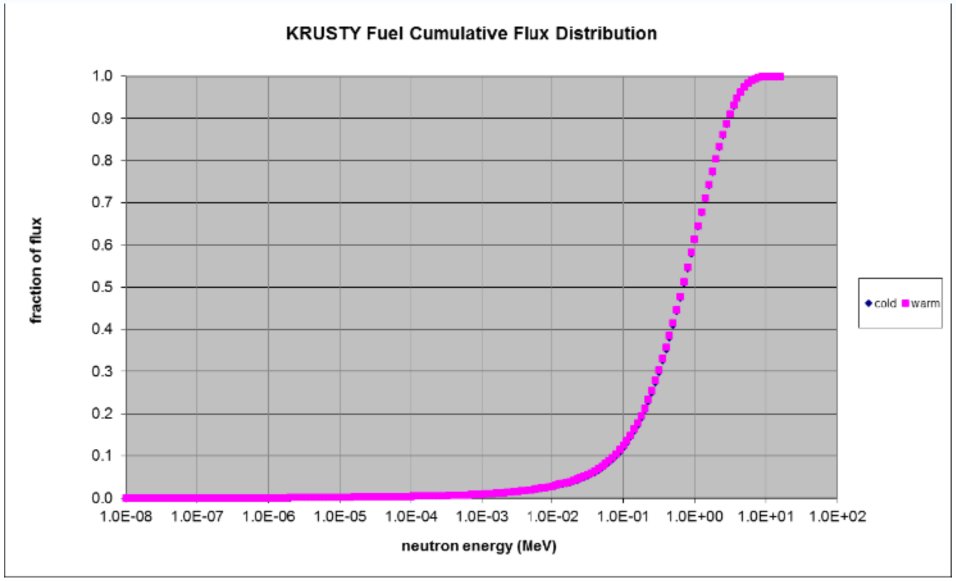
- Beta-effective
  - MCNP kopts card give .00687 +/- .00002
  - MCNP Kcode totnu gives .00689 +/- .00002
    - Totnu = 1 gives .99997+/- .00001
    - Totnu = 0 gives .99308 +/- .00001
  - Using beta-eff = .0069
- Lifetime
  - Average neutron generation time of system = 3.5e-5
  - Fast neutron generation time (fuel and nearby reflector) = 5.5e-8
- Geometrically delayed-neutrons
  - The difference between the fast and average generations times listed above is the effect of neutrons returning from further out in system,
    - The returning neutrons take make longer to cause fission because of the longer distance traveled and slower velocity.
    - By definition, a neutron that has left the core and returned has suffered at least one collision (and often more than one) thus their energy/velocity has been reduced.
  - Geometrically delayed neutron groups are like traditional delayed neutron groups, but they bin neutrons based on the average time it takes a neutrons to cause fission depending on how far out from the core it has traveled.
    - This includes the delayed effect of n2n and photoneutrons.
    - Geometrically delayed groups are very short-lived (on the order of milliseconds) compared to decay delayed-groups (on the order of seconds), and the only impact higher reactivity insertion events.
  - Charts later in the presentation show that the value of neutron lifetime, or the inclusion/omission of geometric groups, has essentially no impact on the integral/macroscopic results.
    - Magnitude of power spike can be reduced, but width of spike (or number of fissions) remains essentially constant

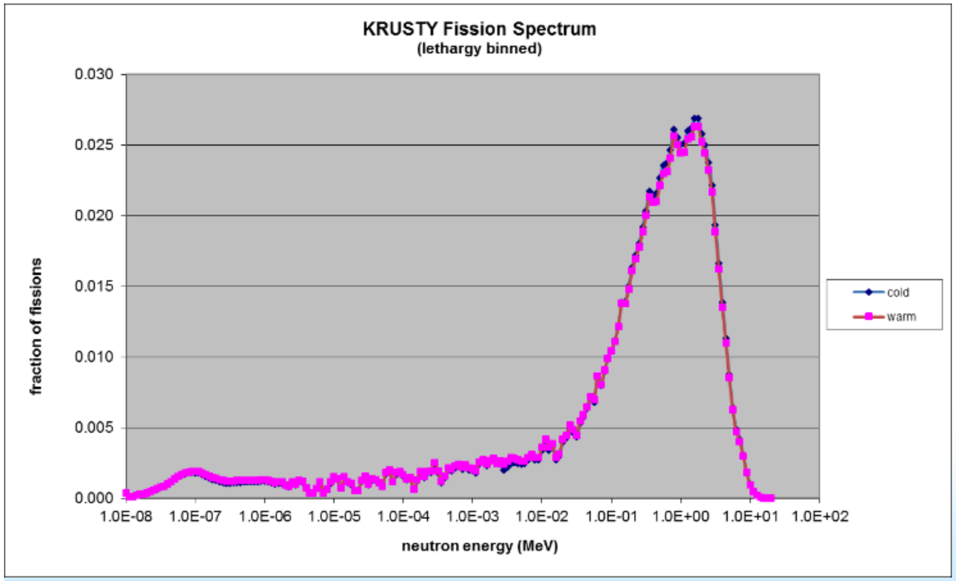
Photoneutrons

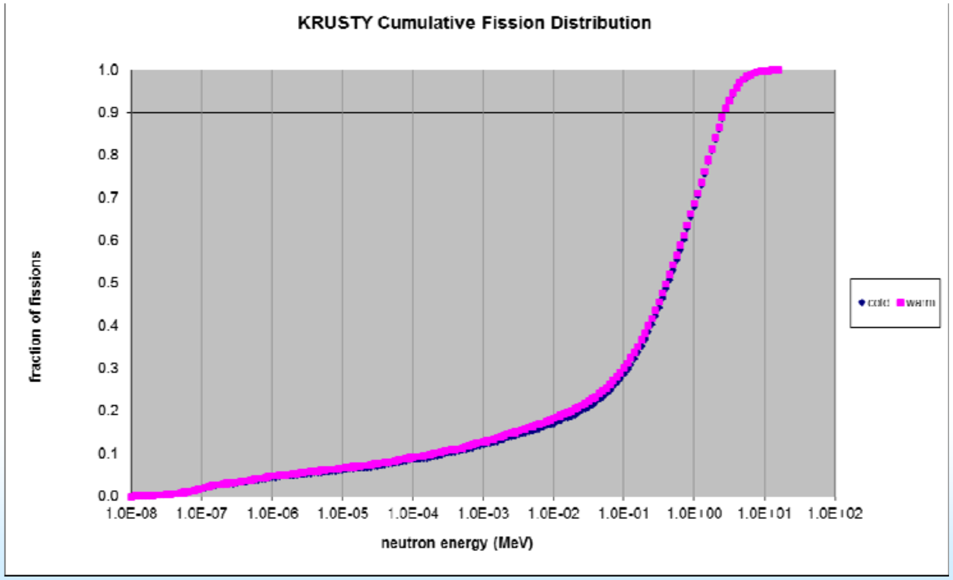
- A high energy photon that hits Be can produce a neutron.
- For KRUSTY, there are 0.000081 photoneutrons for every “standard” neutron.
  - One cent is 0.00007 in K-eff, so in terms of system population you could incorrectly infer that 1 cent of reactivity from photoneutrons
- However, the energy of these neutrons is very low (average energy of ~100 eV), therefore their velocity/flux is low, plus they are created outside of the fuel.
  - More-so, there is a low-energy neutron absorber between radref and fuel (the Haynes230 clamps, the Mo MFI and the SS316 Vessel), so most of these low energy neutrons are not likely to make it back to the core.
    - The axial reflector only has the MFI boundary, but has much lower area that sees the fuel.
- Bottom line is that the <u>worth of photoneutrons was calculated as 0.05 cents +/- 0.20 cents, thus statistically insignificant</u>
  - For academic interest, the photoneutron worth was calculated when voiding out the vessel, MFI and clamps, and the worth went up to 0.5 cents +/- 0.2 cents – so up by an order of magnitude, but barely significant even then.

KRUSTY Spectra – Cold vs Warm

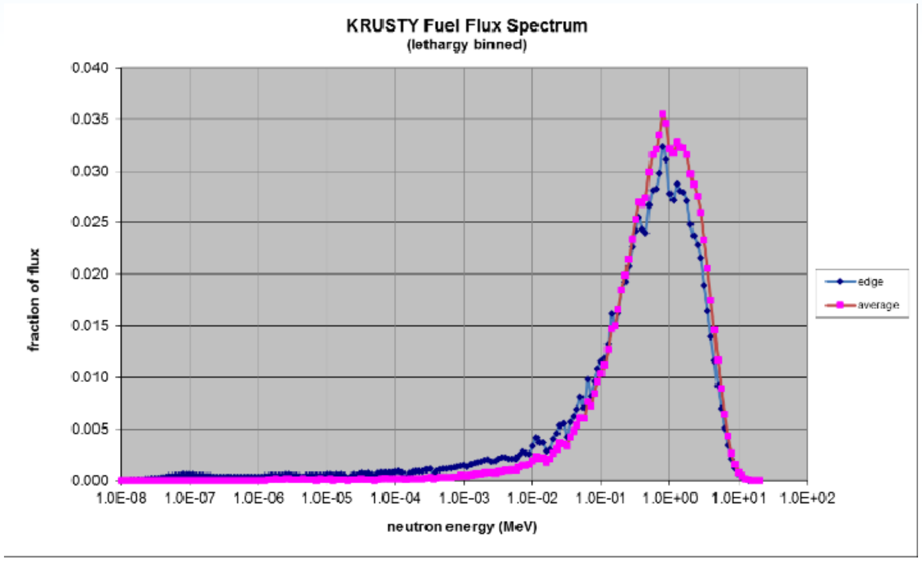


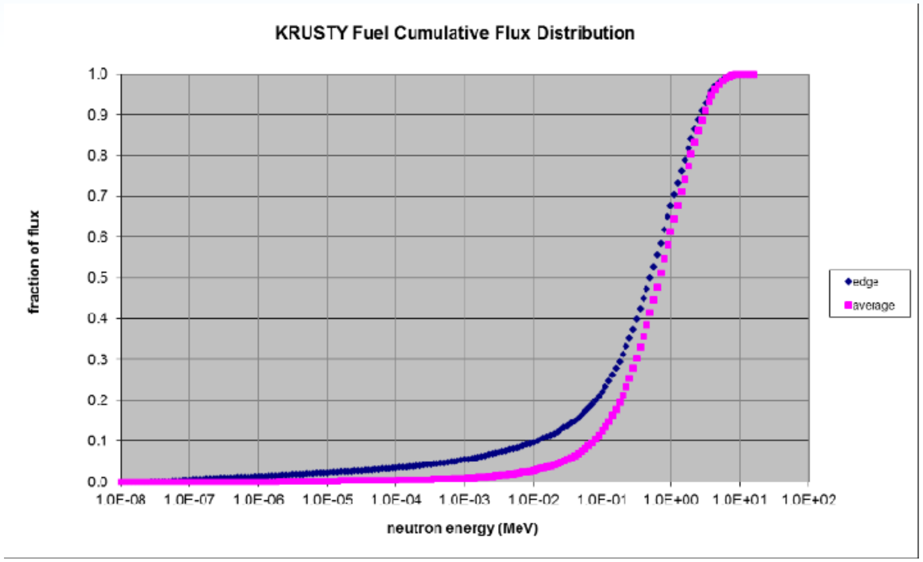


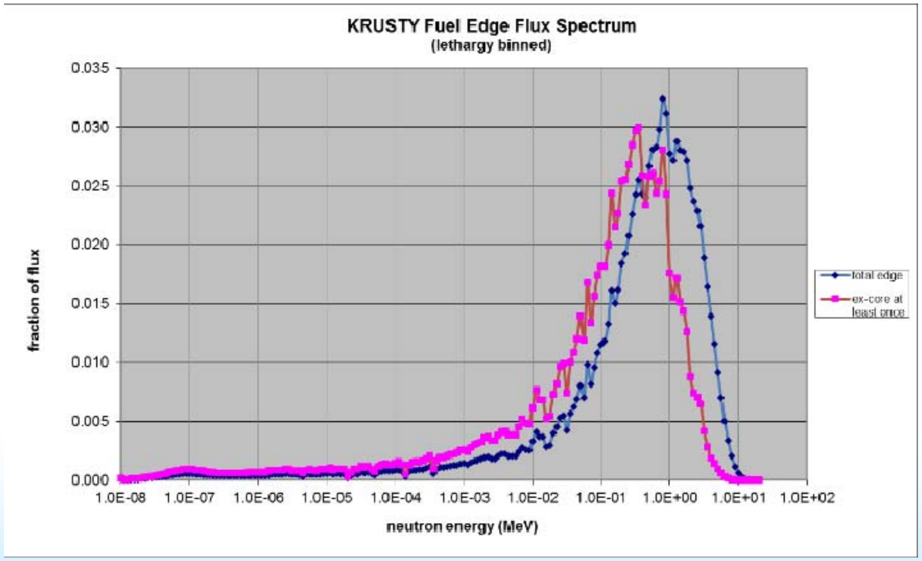


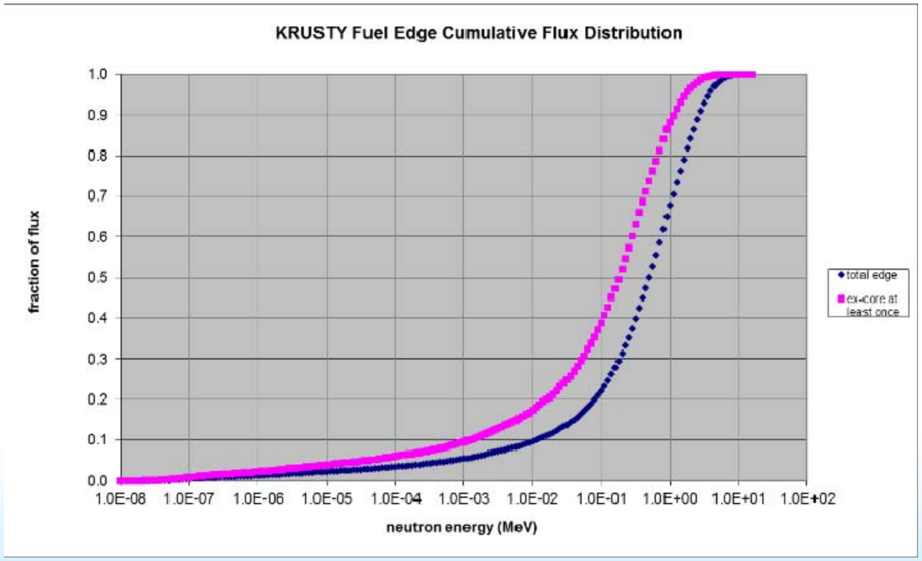


KRUSTY Spectra – Edge Effects

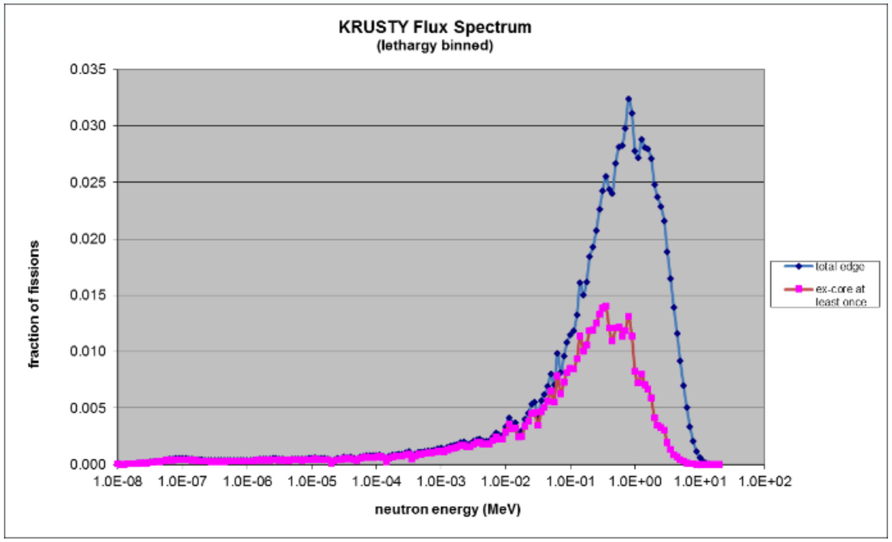


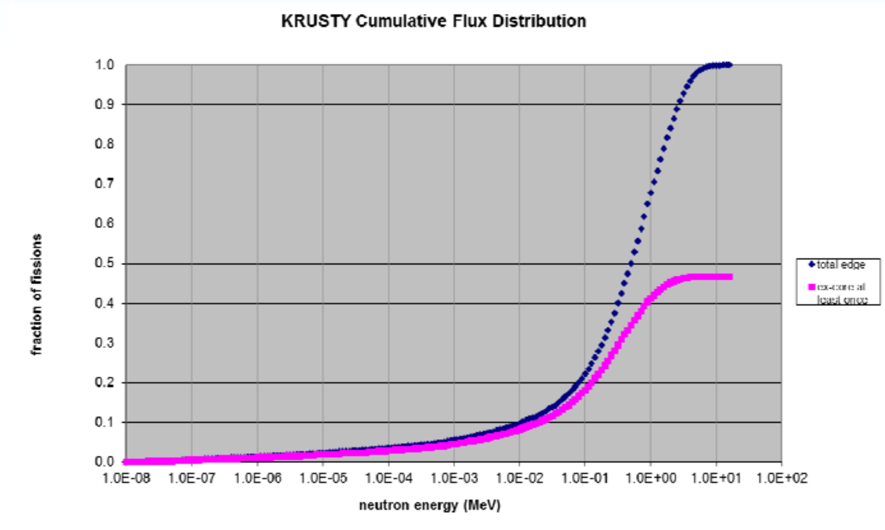






Edge, normalized to total





This shows that almost to 50% of neutrons crossing the outer fuel boundary have been outside of the core at least once.

This does not mean that 50% of those that leave return. Some neutrons will cross the border more than once (e.g. return, leave , return). Also, n2n will add a fair amount of returning neutrons that never “left”.

Reactivity Worth and Feedback Calculations

- KRUSTY is a very compact, fast spectrum reactor,
  - Therefore geometry and density dominate feedback (neutron leakage from core), not cross sections (i.e. nuclear interaction probabilities)
- The "reactivity defect" is the change in k-eff from room-temperature/zero-power to steady-state operation
  - The "temperature defect" is defined as the change in k-eff from room temperature to nominal operating temperature.
    - An integral effect of all temperature changing together.
- The reactivity impact of the following components has been calculated and used; temperature feedback includes changes in density, geometry and cross sections.
  - Physical Inputs
    - Platen Position
    - BeO Radial Reflector Stack-Height
    - B4C Central Rod Height
  - Temperature Feedback (density, geometry, cross sections)
    - Fuel Temperature (as a function of core region)
    - Axial Reflector Temperature
    - Heat Pipe Temperature
    - Core Bracket Temperature
    - Multi-Layer Insulation Temperature
    - Vessel (Core Can) Temperature
    - Radial Reflector Temperature
    - Shield Temperature
  - Power Feedback (function of heat pipe power and pool temperature)
    - Na pool height

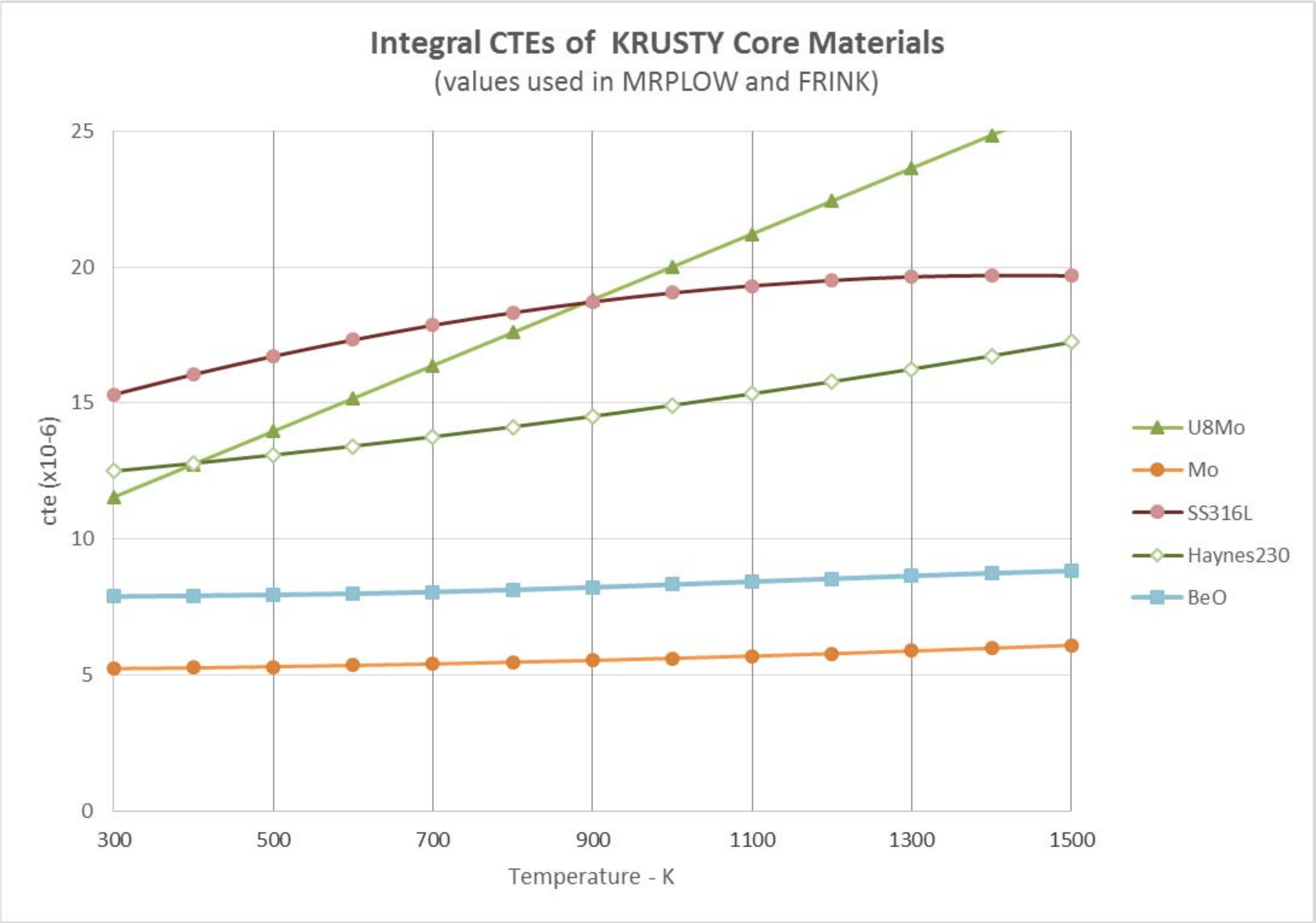
How Temperature Feedback is Applied

- Most reactor kinetics (time dependent) solutions use reactivity temperature coefficients (RTCs) for each individual component.
  - However, the feedback of a component depends on the thermal/geometric state of the balance-of-system.
    - I.e, the fuel reactivity feedback depends on the temperature and position of the reflector, and using a fuel RTC that is only dependent on fuel temperature will miss this 2nd order, or integral effect.
- This 2nd order effect creates potential issues with “reactivity conservation” as a kinetics solution progresses.
  - An ideal solution would calculate k-eff real time along with temperature and geometry changes.
  - This is impractical with a monte carlo code and better approximated with a deterministic code (but still hard to do well regardless).
  - Alternatively, a set of reactivity coefficients could be used that depend on more than one component temperature, but his is also difficult to implement correctly.
  - A good option is to create a lookup table of k-eff versus a matrix of component temperatures
    - If time permits this could be worthwhile, but it can be hard to create enough values to bound all potential transient scenarios (i.e. the temperature profile of a rapid insertion versus a profile during decay power removal).
- Fortunately, the 2nd order effects are small for KRUSTY.
  - The fuel reactivity feedback varies by <1% if the balance of system is cold or at nominal operating temperature.
    - Therefore, individual component RTCs should work well.
- To compensate for the small integral effect, small adjustments are made to the individual component RTCs such that keff at nominal operating temperature matches the mcnp (all components warm) calculated keff.
  - In other words, the sum of each “RTC times the temperature change” is equal to the calculated “temperature defect” in going from room to nominal operating temperature.

Component Reactivity Feedback Calculations

- MRPLOW creates MCNP decks to calculate reactivity feedback
  - MRPLOW calculates temperatures with simple 1D steady-state equations OR temperatures can be input based on results from other codes
  - MRPLOW applies material expansion coefficients to shift geometry
    - Most components are freely expanded, and a warning is printed out if interference occurs.
    - For components expected to have interference, the code is hardwired to specify which component yields/strains, as opposed to the component that “gets its way”
  - MRPLOW specifies temperature dependent cross sections
  - MRPLOW also creates decks to find coolant void coefficient
    - The height of the pool has significant worth (from 5 to 20 cents depending on heat pipe fill and temperature/density.
    - Reactivity temperature coefficients are calculated with a “full” Na pool (cold, zero-power), and overall system reactivity is adjusted by subtracting the reactivity effect of the pool position (at the corresponding power/temperature).
  - Other coefficients, like regional feedback within the fuel, are performed by modifying MCNP decks “by hand”.
- In all cases, it is most important to confirm mass conservation!
  - The code uses separate calculations for dimensional changes and density changes, if the mass ends up the same then they were likely done consistently (both would have to be wrong for answer to be right).
  - As the ultimate check, a tool is used the utilizes MCNP in source mode, to determine the actual volume/mass of every cell, component and material
    - Because MCNP isn’t smart enough to figure volumes of complex geometries on its own)

Linear Thermal Expansion Coefficients



Mo and BeO are small, while U8Mo, Haynes 230, and SS316 are all in the same ballpark. U8Mo CTE is very large at higher temperature, which is great in terms of providing stronger negative feedback at high temperatures. The lower CTE at low temperatures is also ideal so that less excess reactivity is required to bring the reactor to high temp. U8Mo is gamma phase.

Temperature Dependent Cross Sections

- Continuous energy MCNP cross sections generated by NJOY/ACER
- Cross section set called SPACE07
- ~360 isotopes
  - ENDF/B-VII
  - If xs not available in ENDF/B-VII then use
    - JEF2.2, 3.0
    - JENDL3.2, 3.3
- 25 temperatures
  - 300K through 3000K
    - Every 50 degrees <1000 K (for thermal systems we sometimes use 10 K intervals in regions of interest)
    - Every 100 degrees >1000 K
  - "logic" based suffixes
    - 750K → .75c
    - 1500K → .15c
    - Am242m → 95342
- Thermal scattering corrections, S(a,b), generated at 100 K intervals.

Temperature Dependent Cross Sections

- SPACE07 is based on ENDF7.0, and is planned to be eventually updated to ENDF7.1.
  - For now, a bias is established between ENDF7.0 and ENDF7.1 by running both at temperatures that exist in both libraries (i.e. room, 600K , 900K).
  - For the KRUSTY experiment END71 results in keff ~18 cents higher, but the biggest difference is caused by beryllium.
    - The details of ENDF7.0 and ENDF7.1 differences are presented near end of presentation.
- When MRPLOW writes and MCNP deck, it writes the material card cross section suffix for the closest cross section to the calculated material temperature.
  - Introduces slight error in “warm” k-eff, depending on how far calculated/input component temperatures are from the discrete xs values.
  - When generating reactivity coefficients, temperatures are selected at the exact cross section intervals.
- MRPLOW also writes a TMP card specification for each cell based on the calculated temperature.
  - This is used to modify the classical nuclear collision models, which generally don’t matter in KRUSTY, because it has a very fast neutron spectrum.

KRUSTY Reactivity Calculation Notes

- This analysis is for case krst5b
  - This was a design lock of 8/27/16
    - Although, despite best intentions, the design (and how it performs) can potentially change up until the moment all parts are fabricated and the experiment is actually run; the hope is that no changes will occur that have a significant impact of reactivity – if they do, some work will have to be redone.
    - Good news, no changes required since (from 8/27 to 10/11).
- The nominal operating condition of krst5b that these calculations are based on assumes:
  - Full temp/power platen position = -0.50 cm
  - Beo platen stack = 30.48 cm (12” fully loaded)
  - BeO shim stack = 2.54 cm (1” of a possible 2”)
  - Central B4C stack = 0.0 cm (i.e. no b4c in central hole)
- All cases calculated with MCNP6
  - Cases are run with 4 billion source neutrons
  - This gives an error of ~0.00001 in k, or ~0.1 cents
  - This error is low enough to be negligible compared to other uncertainties.
    - E.g., densities, tolerances, cross sections, tolerance in platen position, error in measurements, etc.
  - If an error is not listed on a result (which is the bulk of them), then it can be assumed it is ~0.00001 in keff.

Operating Defect – From "Inside-Out"

	Temp(K)	keff	dK/K	cents	Ave CTE (cent/K)
cold, zero-power state	297.0	1.01190			
cold pool drop (15.25cm to -4.75cm)		1.01129	-0.00060	-8.7	
expand fuel	1074.7	1.00101	-0.01022	-148.1	-0.1904
warm fuel cross sections	1100.0	1.00033	-0.00068	-9.8	-0.0123
expand heatpipes	1051.0	1.00030	-0.00003	-0.4	-0.0006
warm heatpipe cross sections	1100.0	1.00022	-0.00008	-1.2	-0.0014
expand bracket	1045.0	1.00017	-0.00005	-0.7	-0.0010
warm bracket cross sections	1000.0	1.00000	-0.00017	-2.5	-0.0035
expand axref	413.0	0.99999	-0.00001	-0.1	-0.0012
warm axref cross sections	400.0	1.00001	0.00002	0.3	0.0028
expand mfi	805.7	1.00001	0.00000	0.0	0.0000
warm mfi cross sections	800.0	0.99996	-0.00005	-0.7	-0.0014
expand vacves	373.5	1.00012	0.00016	2.3	0.0303
warm vacves cross sections	350.0	1.00013	0.00001	0.1	0.0027
expand radref	311.0	1.00005	-0.00008	-1.2	-0.0828
warm radref cross sections	300.0	1.00005	0.00000	0.0	0.0000
Expand platen shield/structure	309.4	1.00007	0.00002	0.3	0.0234

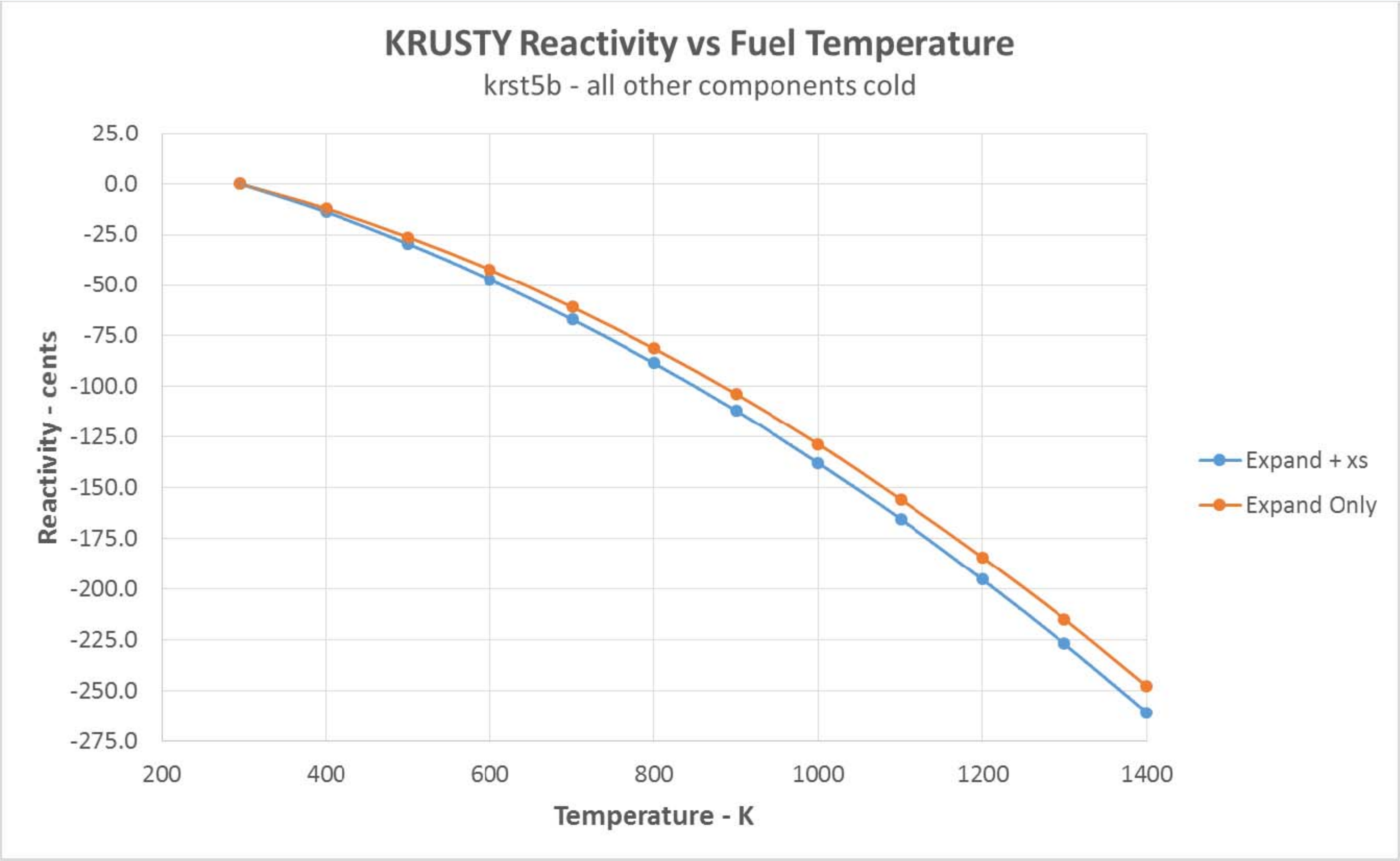
The order of component temperature change is roughly based on sensitivity to changes in core power.
Cross section temperature changes only possible every 50 degrees.
Statistical error in cents calculation +/- ~0.2 cents)

Net Operating Defect, and the Effect of Heating Order on Worth

		Inside-Out			Outside-In		
	Temp(K)	cents	% of temp defect	% defect expand+xs	cents	% of defect	% defect expand+xs
expand fuel	1075	-148.1	91.5%	97.6%	-147.7	90.4%	96.7%
warm fuel cross sections	1100	-9.8	6.1%		-10.3	6.3%	
expand heatpipes	1051	-0.4	0.3%	1.0%	-1.7	1.1%	2.0%
warm heatpipe cross sections	1100	-1.2	0.7%		-1.6	1.0%	
expand bracket	1045	-0.7	0.4%	2.0%	-0.7	0.4%	1.6%
warm bracket cross sections	1000	-2.5	1.5%		-1.9	1.1%	
expand axref	413	-0.1	0.1%	-0.1%	-0.6	0.4%	0.2%
warm axref cross sections	400	0.3	-0.2%		0.3	-0.2%	
expand mfi	806	0.0	0.0%	0.4%	0.0	0.0%	0.3%
warm mfi cross sections	800	-0.7	0.4%		-0.4	0.3%	
expand vacves	374	2.3	-1.4%	-1.5%	1.9	-1.1%	-1.1%
warm vacves cross sections	350	0.1	-0.1%		-0.1	0.1%	
expand radref	311	-1.2	0.7%	0.7%	-0.9	0.5%	0.5%
warm radref cross sections	300	0.0	0.0%		0.0	0.0%	
platen shielding	309	0.3	-0.2%	-0.2%	0.3	-0.2%	-0.2%
Total Temperature Defect		-161.8			-163.5		
pool up (-4.75cm to 15.25cm)		-8.7			-7.0		
Total Operating Defect		-170.5			-170.5		

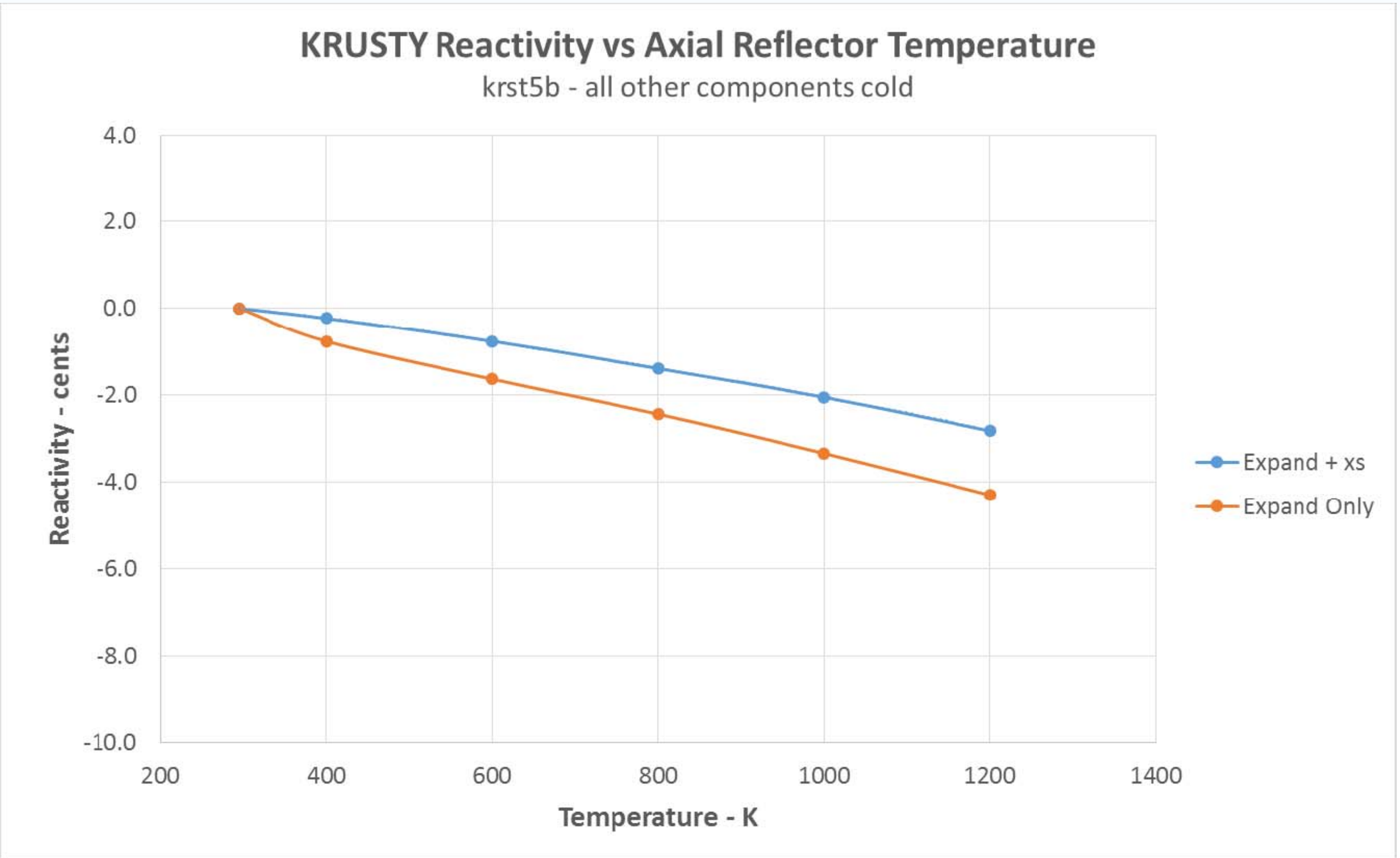
The worth of component heating is rather insensitive to the balance of system; except for the heat pipes, due to the interrelation of the pool height. The fuel temperature defect is a smaller fraction when the balance of system is cold, because a cold reflector is more likely to reflect a leaking neutron back to the core; however, total reactivity lost due to fuel heating is higher for inside-out, because the full-height Na pool is not present to “save” escaping neutrons.

Fuel Temperature Worth



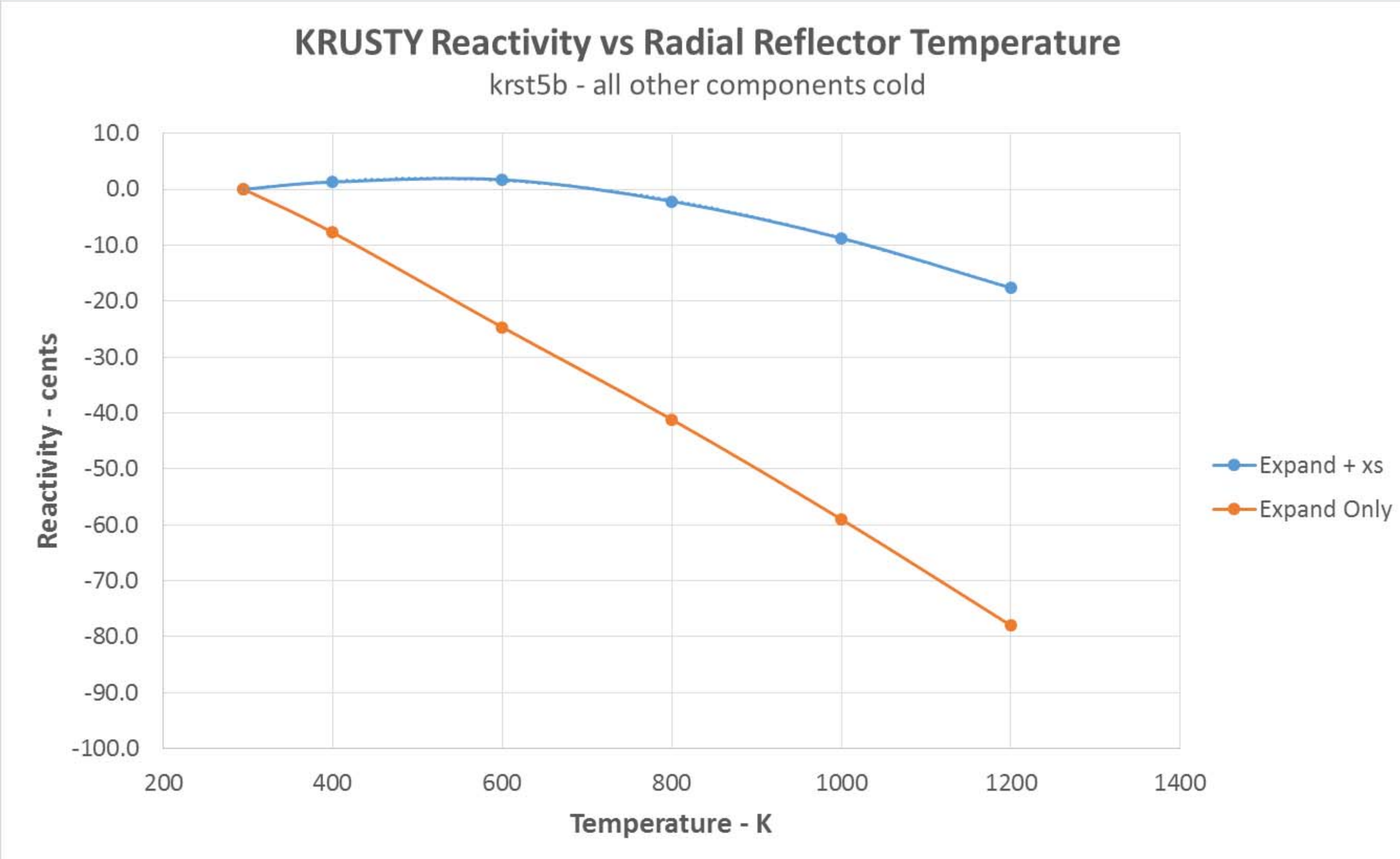
Worth is dominated by expansion coefficient of U10Mo. Warmer cross sections add additional negative feedback because Doppler broadening of U235+U238+Mo capture has more effect than Doppler broadening of U235+U238 fission.

Axial Reflector Temperature Worth



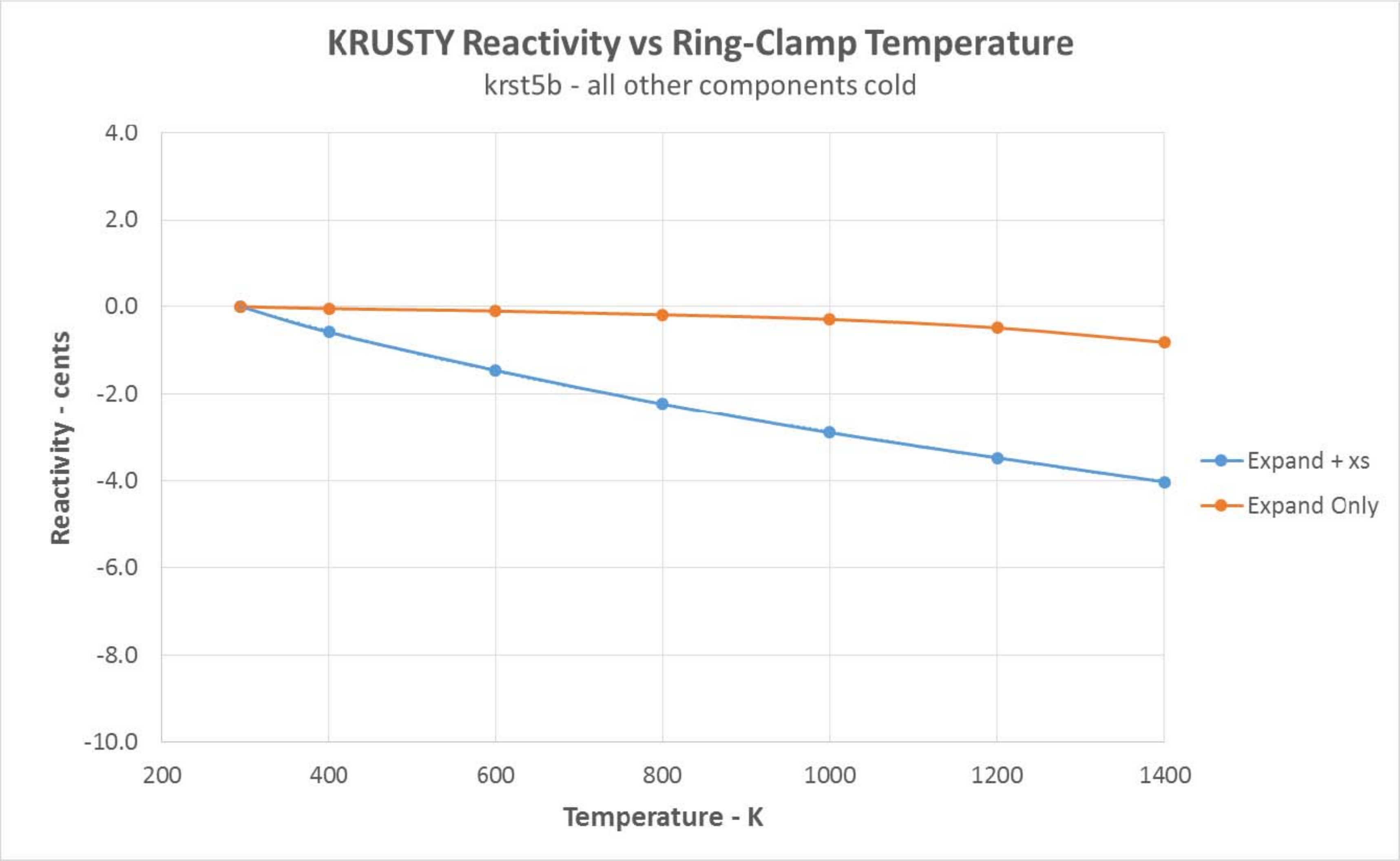
The effect of axref temperature is small. The cross sections provide positive feedback, but the expansion effect is greater, this providing overall negative feedback. Higher temperature reflector cross sections increase reactivity because less-moderation increases the fission-to-capture ratio in the fuel. Note that this calculation also includes the effect of heating the small mass of Mo mli between the fuel and axref..

Radial Reflector Temperature Worth



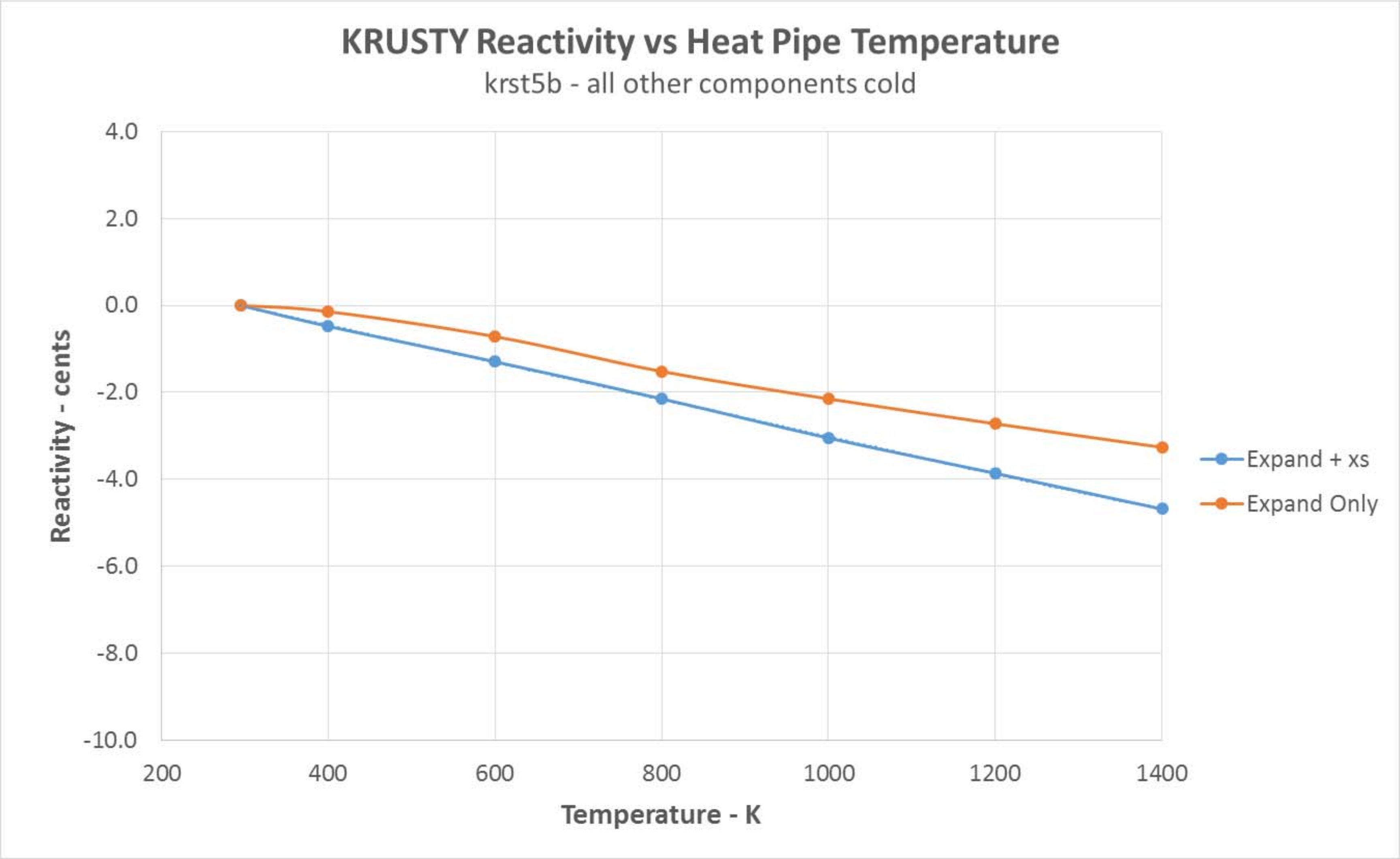
As with the axial reflector, expansion provides negative feedback and cross sections provide positive feedback – but in this case the cross section effect is greater, thus initially providing overall positive feedback (at low temperatures). This is because there are absorbers (vessel/brackets) between the radref and the fuel (notably W in Haynes230); therefore, less-moderated neutrons are more likely to find their way back to the core.

Core-Clamp Temperature Worth



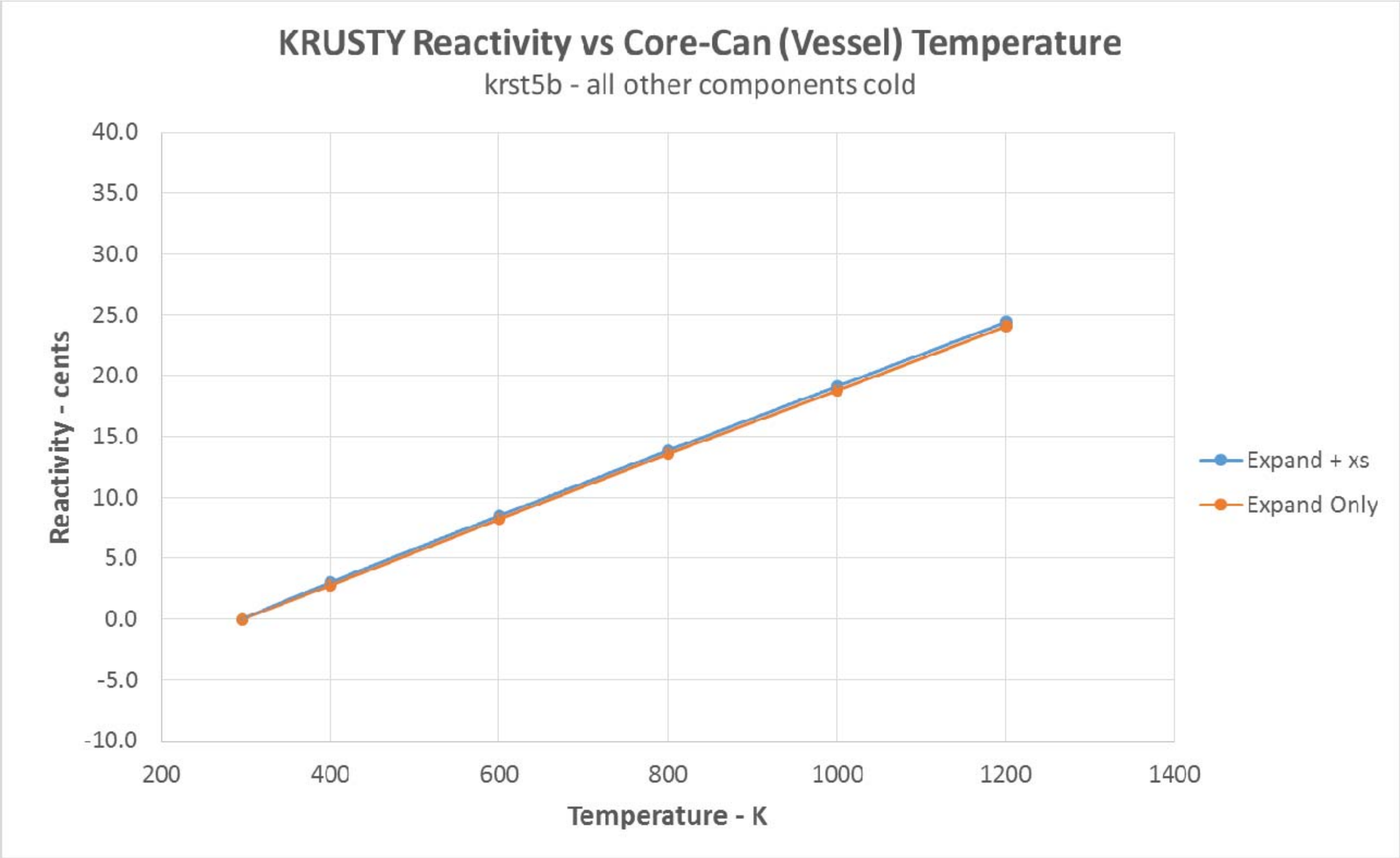
The expansion of the Haynes-230 rings has little effect. Increased leakage probably balances decreased capture, and more importantly smear density of Haynes 230 between the core and reflector does not change There is however, a significant drop in reactivity with cross sections, due to Doppler broadening of capture cross sections, mostly of the tungsten.

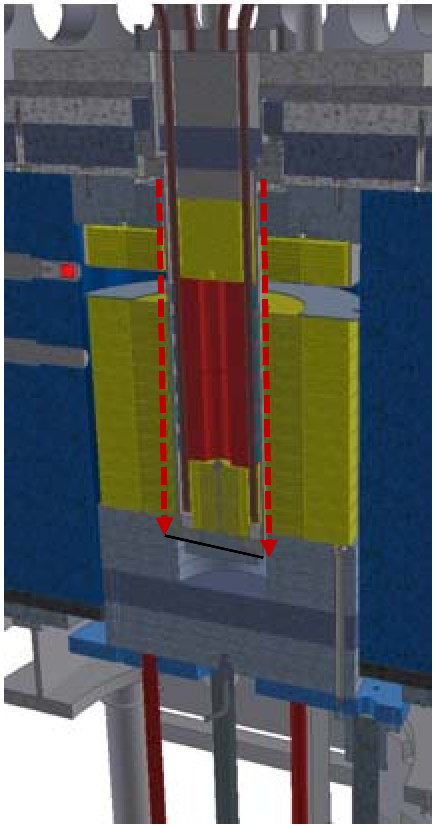
Heat-Pipe Temperature Worth



This worth is calculated with a full-height Na pool, thus there is a significant drop in reactivity with the sharp drop in Na density from frozen (.929 g/cc) to operating (.763 g/cc). In addition, Doppler broadening of SS316 and the Na capture causes a further drop in reactivity.

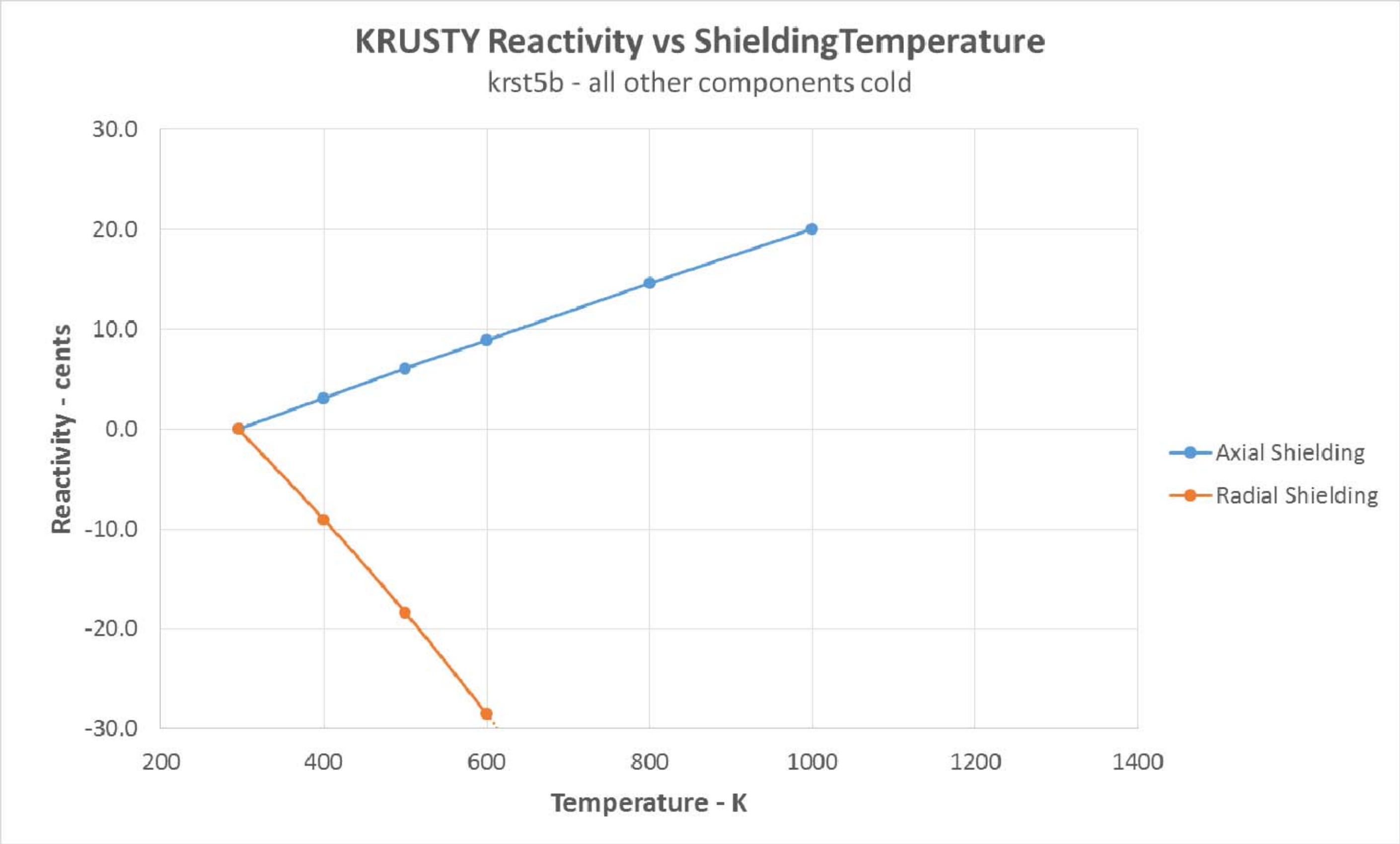
Core-Can (Vacuum Vessel) Temperature Worth

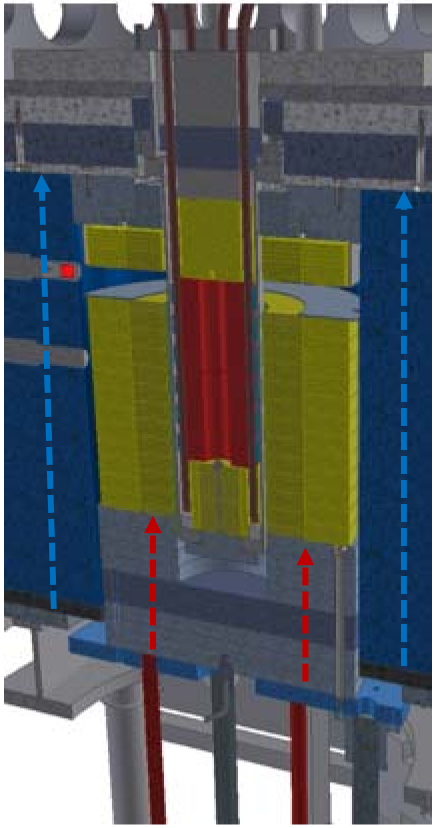




Nominally, the change in temperature of the core-can vessel is negligible – a balance between the increased leakage, decreased macroscopic capture XS (density), with a small increase in microscopic capture XS (Doppler); HOWEVER, expansion of the core-can lowers the fuel within the reflector assembly (dashed red arrows), which has the same effect as raising the platen, thus an increase in reactivity. Fortunately, the vessel should not heat much, predicted max rise of ~100 K.

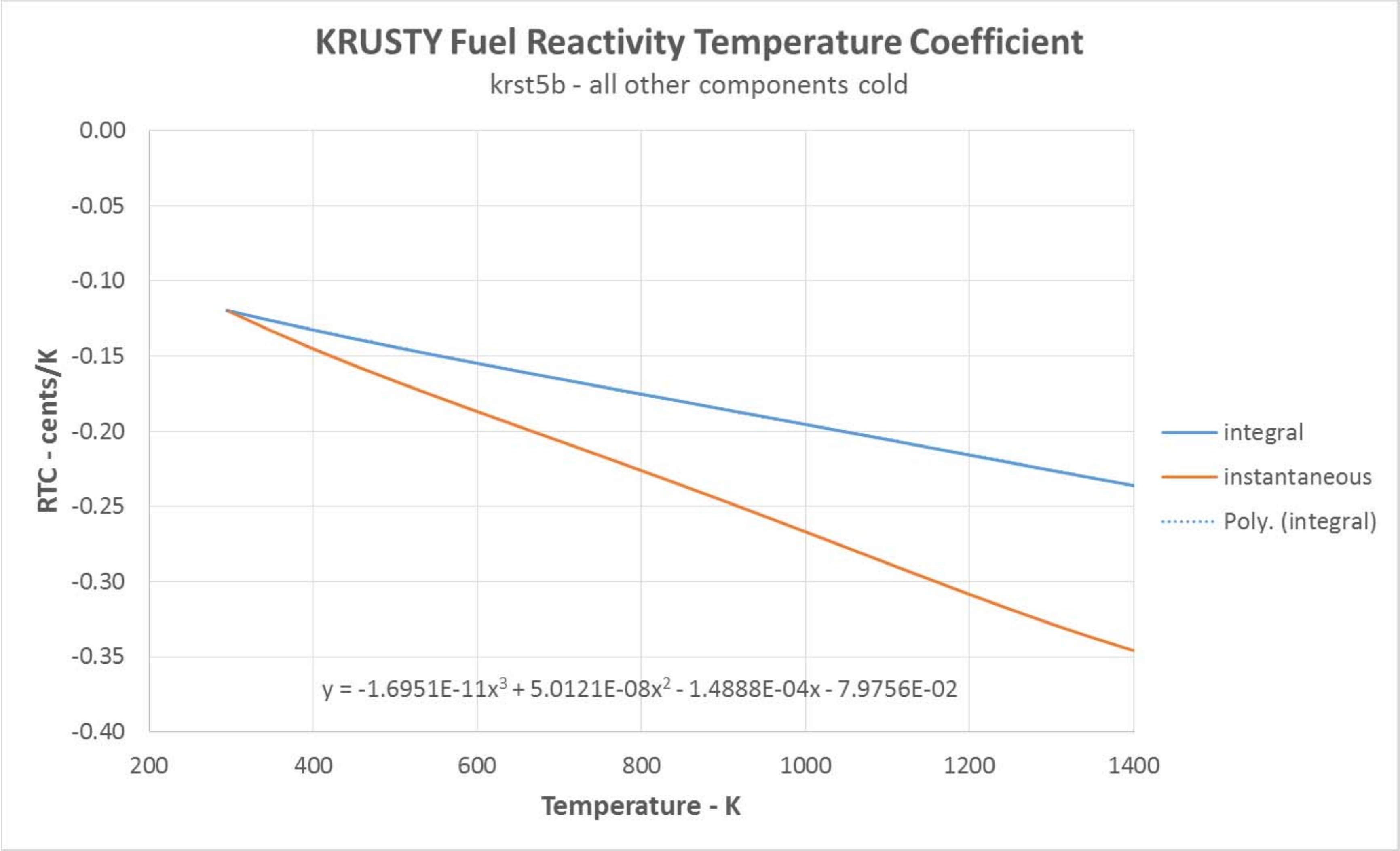
Shielding Temperature Worth





Changing the shielding temperature has the same effect as core-can, in that expansion moves the location of the fuel relative to the reflector (like moving platen). Heating the axial shielding raises the reflector relative to fuel (dashed red arrows), while heating the radial shield raises the vessel, thus fuel relative to the reflector/platen (dashed blue arrows). The worth of these components is significant, but the temperature rise of the shielding should be very small (axial shielding by 10s of degrees, radial shielding a few degrees max).

Fuel Reactivity Coefficient

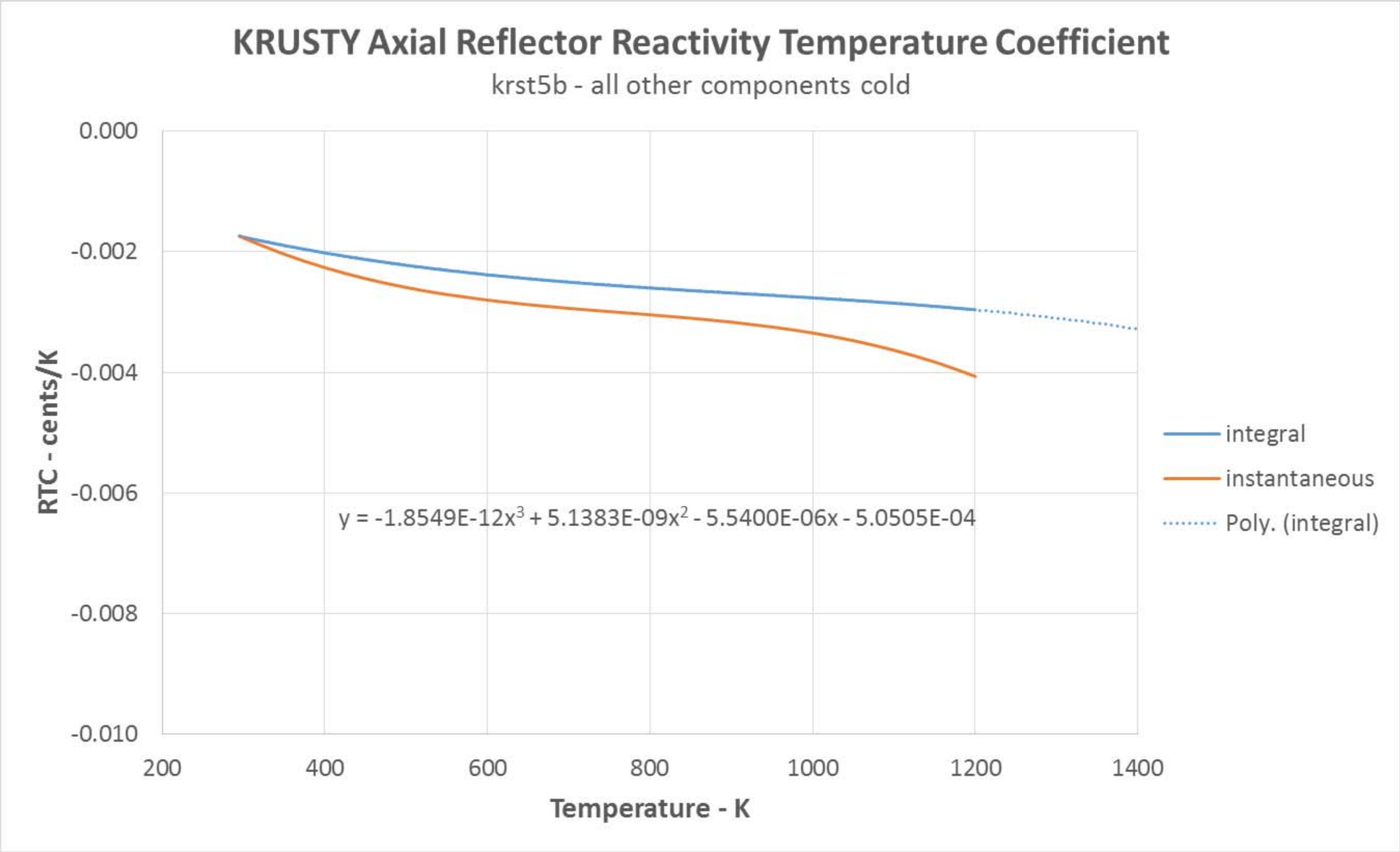


The integral form of RTC applies the total delta-T from operating temperature. The instantaneous RTC is the effect at a specific temperature (thus is the slope (derivative) of the worth vs temperature). The integral value is applied in FRINK to ensure conservation of feedback (i.e. applying instantaneous RTC can cause step-to-step numerical/round-off errors, similar to why integral CTE is generally used). Polynomial is value used in FRINK.

Regional Fuel Feedback

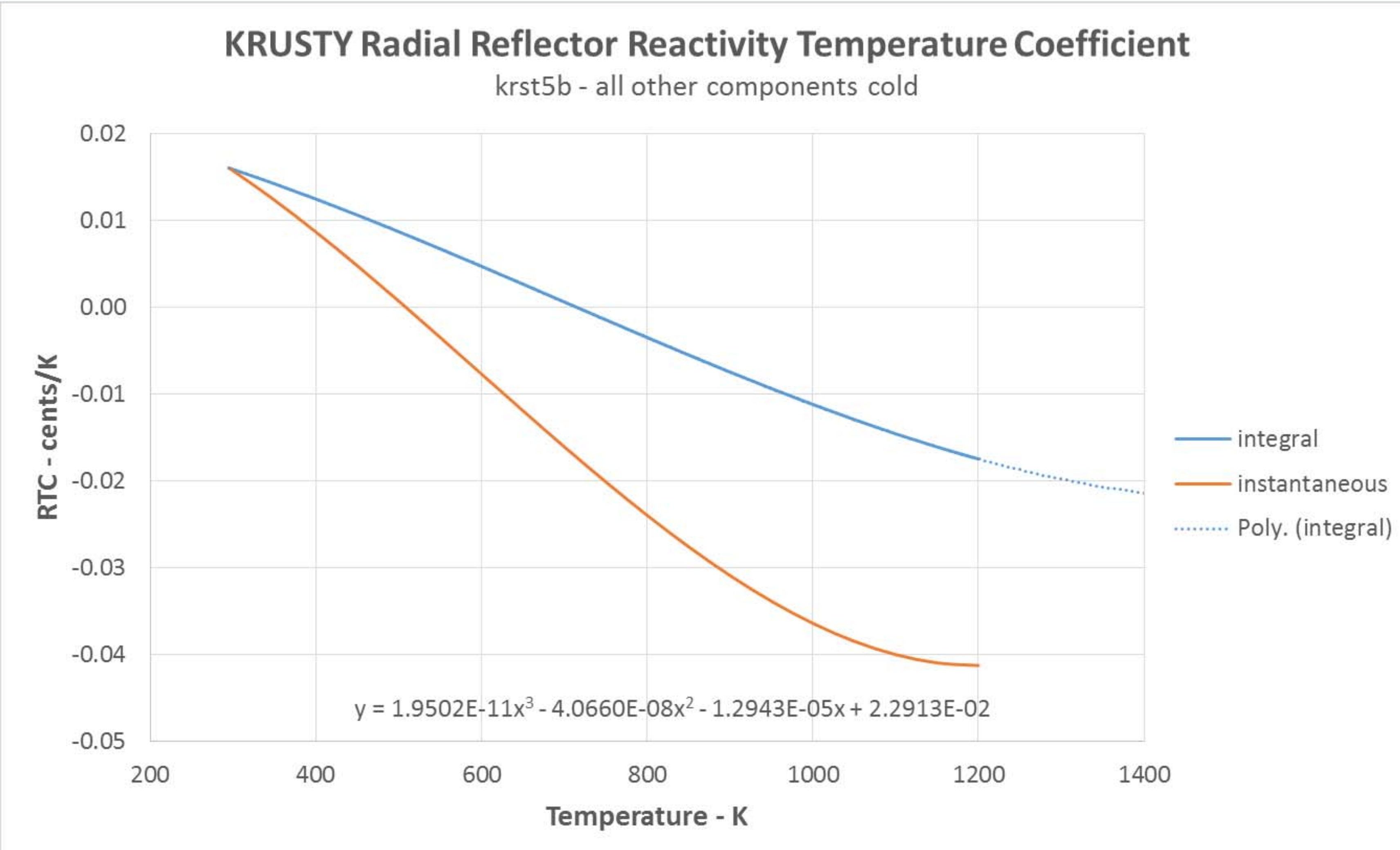
- The fuel reactivity is calculated as a lump parameter, but a change in temperature in one region might have more impact that a change in another.
- MCNP calculations were performed to measure the change in keff by changing the temperature of specific regions of the fuel.
  - With straight keff calcs, not sensitivity or adjoint solutions
- Fuel was separated into 6 regions axially and 4 regions radially.
  - Axial sensitivity calcs were performed separately from radial calc.
- The order of expansion was varied, top-to-bottom, bottom-to-top, inside-out and outside-in.
  - The difference in the worth of the regions did not change much; i.e. their worth was not highly sensitive to the temperature of the regions surrounding them.
- The net result was that the worth of each region was almost identically correlated with the power peaking factor of that region.
  - FRINK thus uses the power peaking factors to define how much of the fuel reactivity feedback is applied to each region.
    - A flag can likewise turnoff this regional feedback, and the 2 can be compared to determine effect – if difference is substantial, more sophisticated method can be considered.

Axial Reflector Reactivity Coefficient



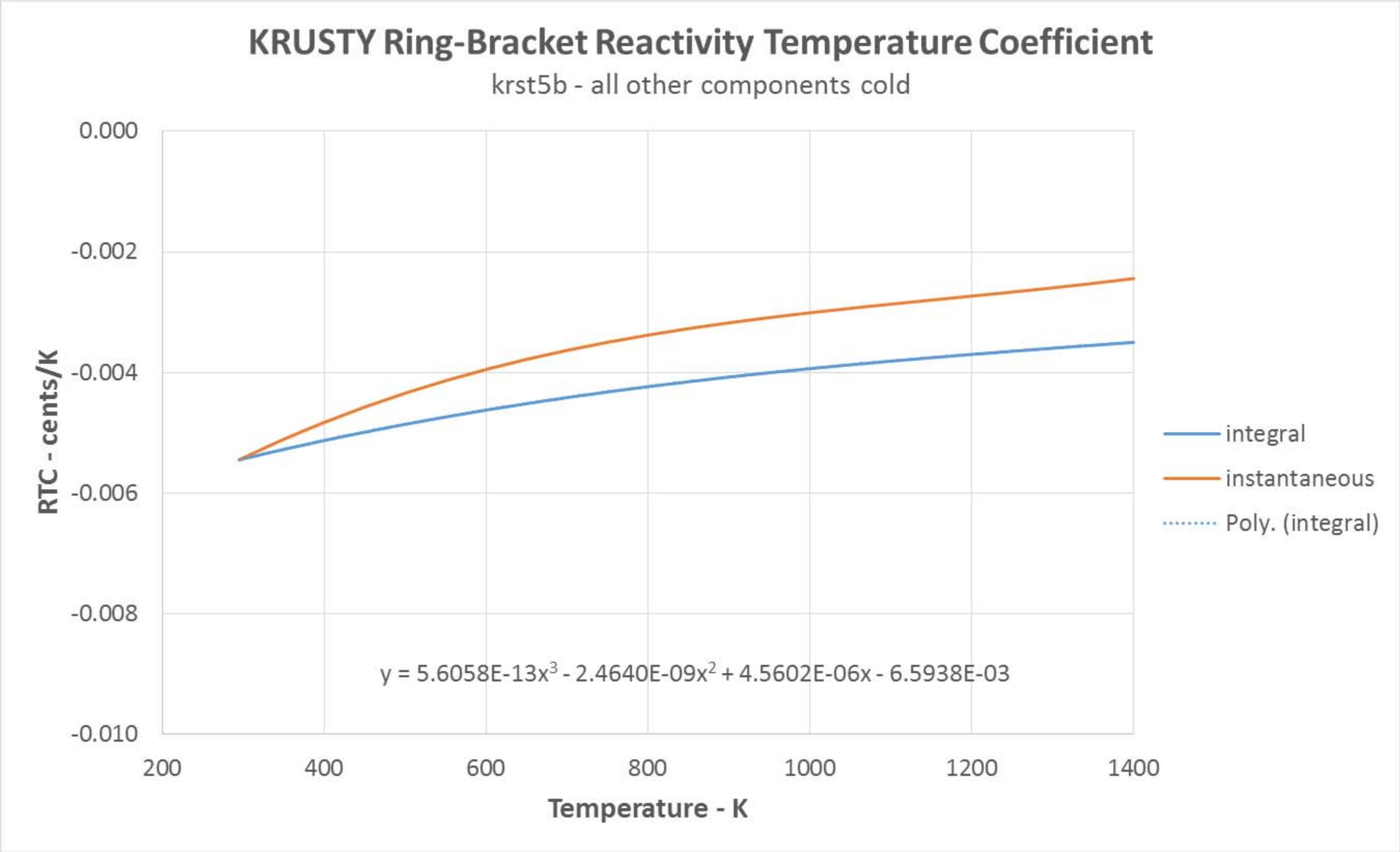
The integral form of RTC applies the total delta-T from operating temperature. The instantaneous RTC is the effect at a specific temperature (thus is the slope (derivative) of the worth vs temperature. The polynomial is used in FRINK.

Radial Reflector Reactivity Coefficient



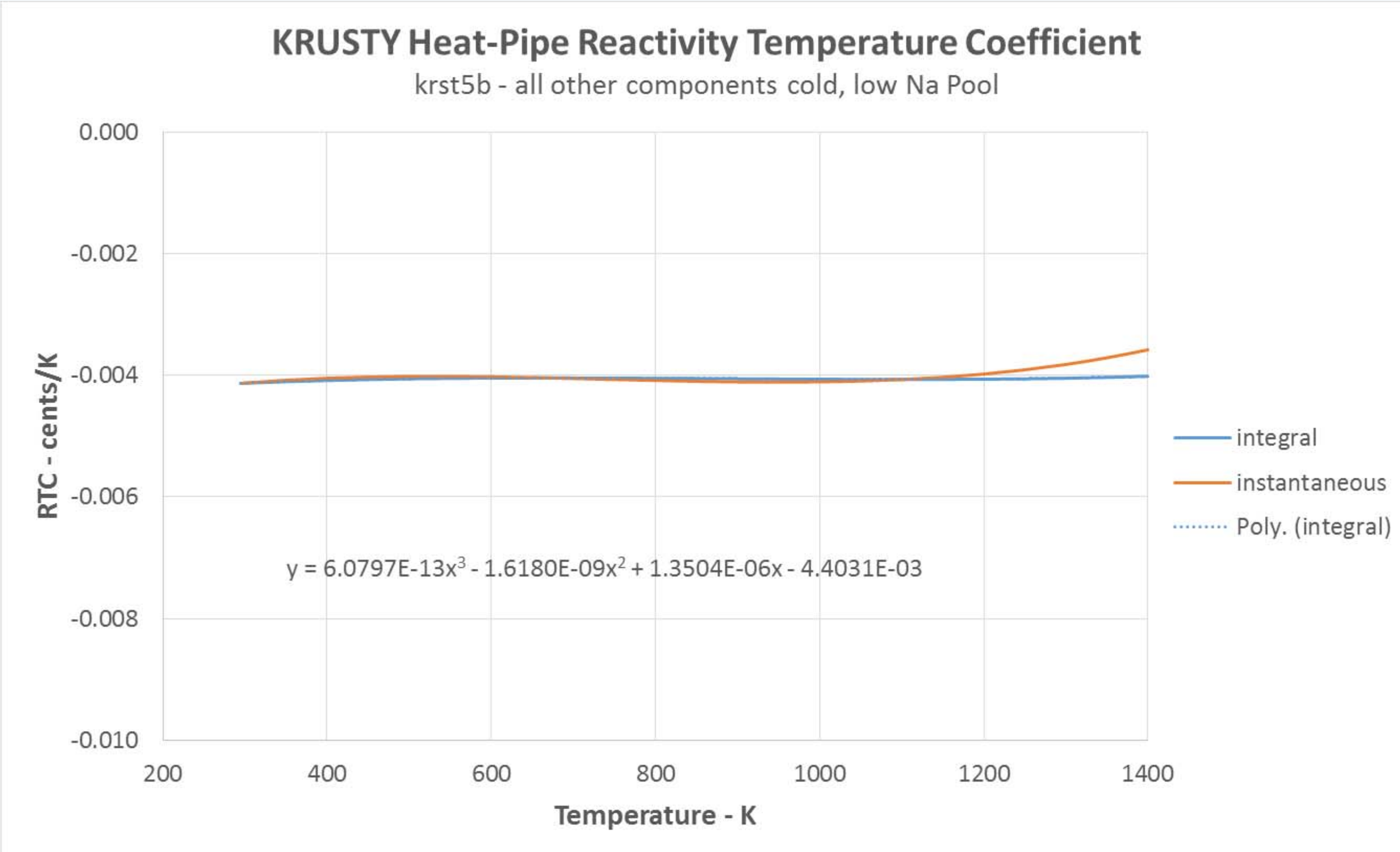
Note the positive value at low temperature as noted on the previous slide that shows worth, recall that the instantaneous RTC is the slope (derivative) of the worth vs temperature.

Core-Clamp Reactivity Coefficient



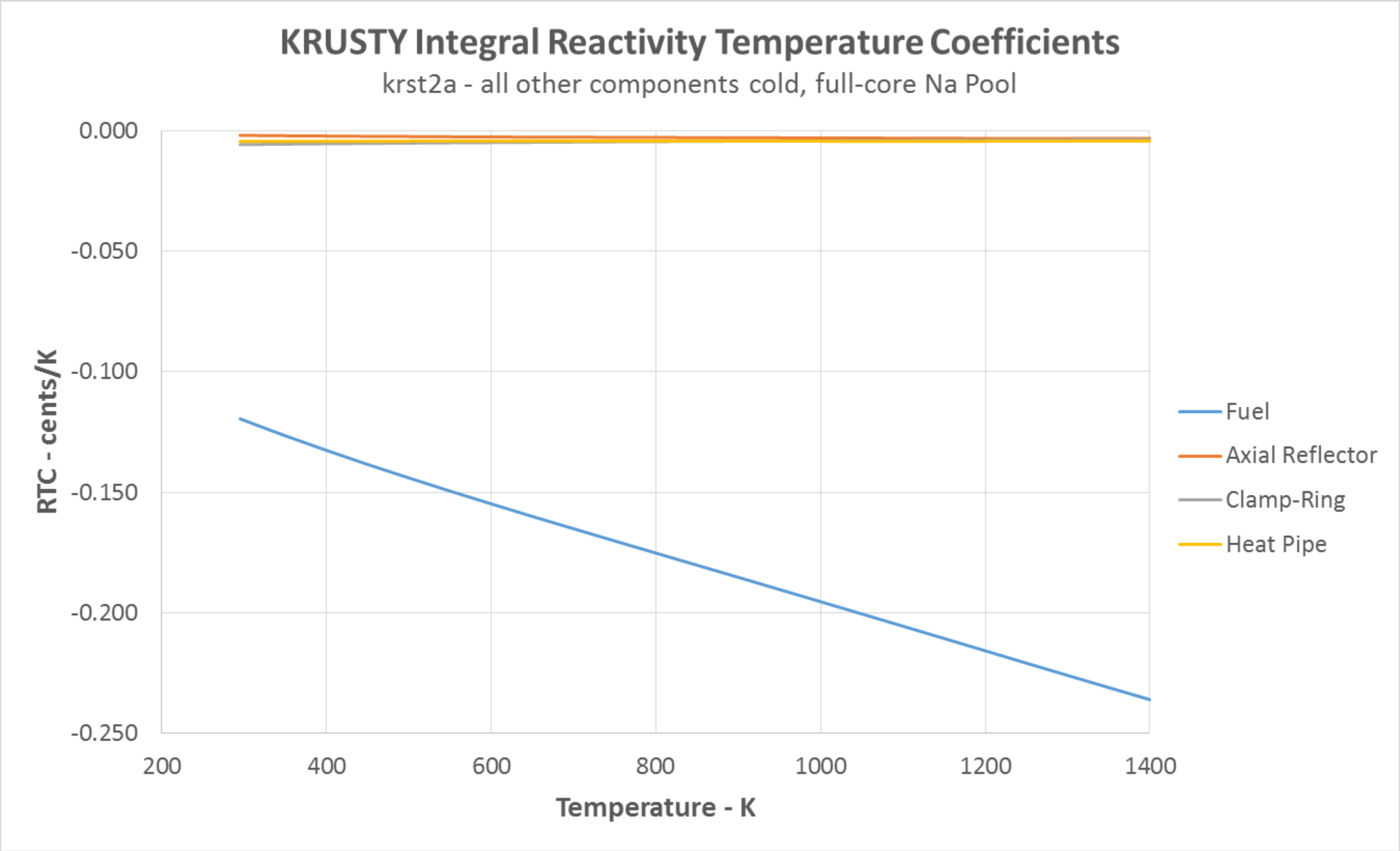
The integral form of RTC applies the total delta-T from operating temperature. The instantaneous RTC is the effect at a specific temperature (thus is the slope (derivative) of the worth vs temperature. The polynomial is used in FRINK.

Heat Pipe Reactivity Coefficient



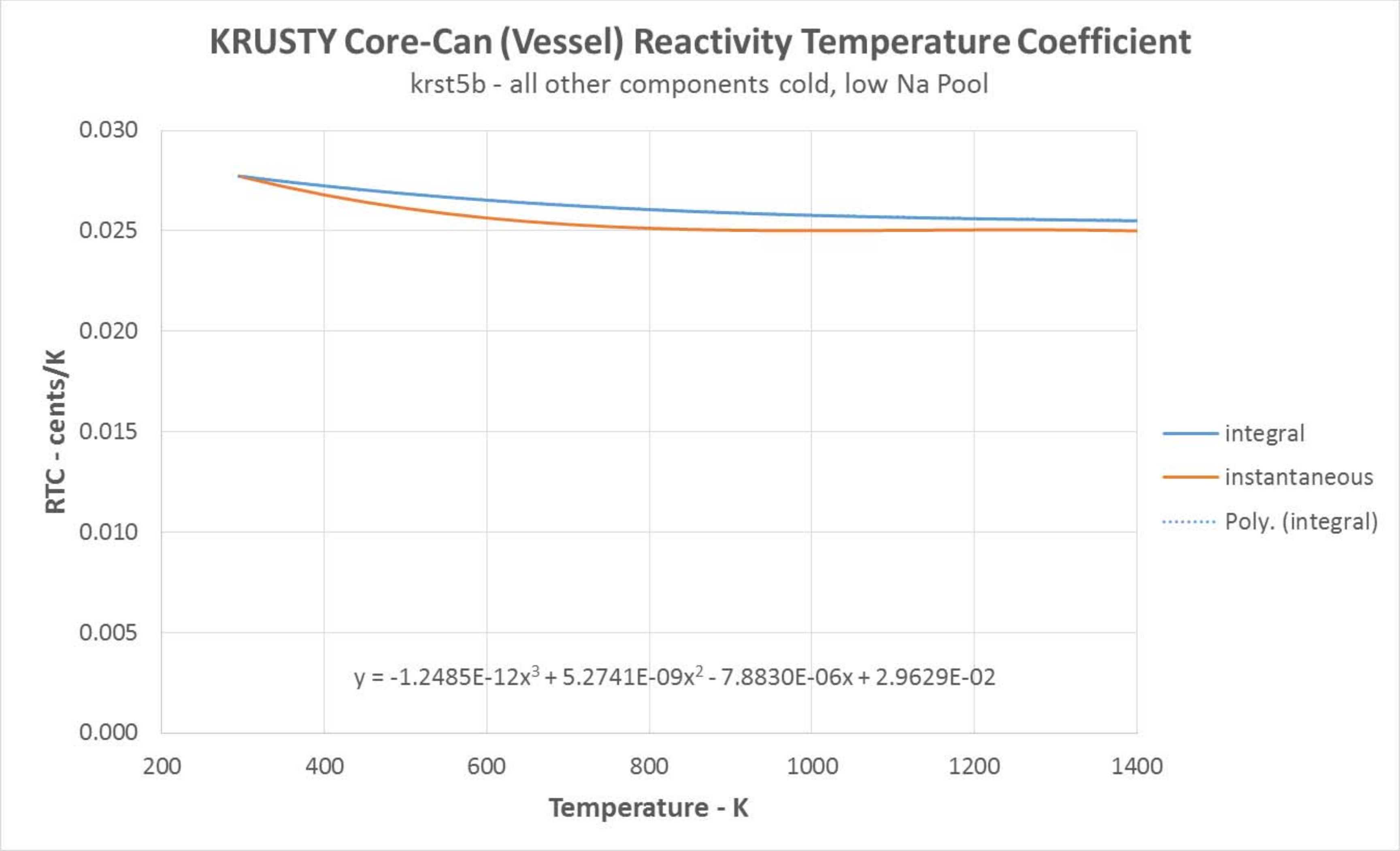
The integral form of RTC applies the total delta-T from operating temperature. The instantaneous RTC is the effect at a specific temperature (thus is the slope (derivative) of the worth vs temperature. The polynomial is used in FRINK.

Comparison of Core RTCs



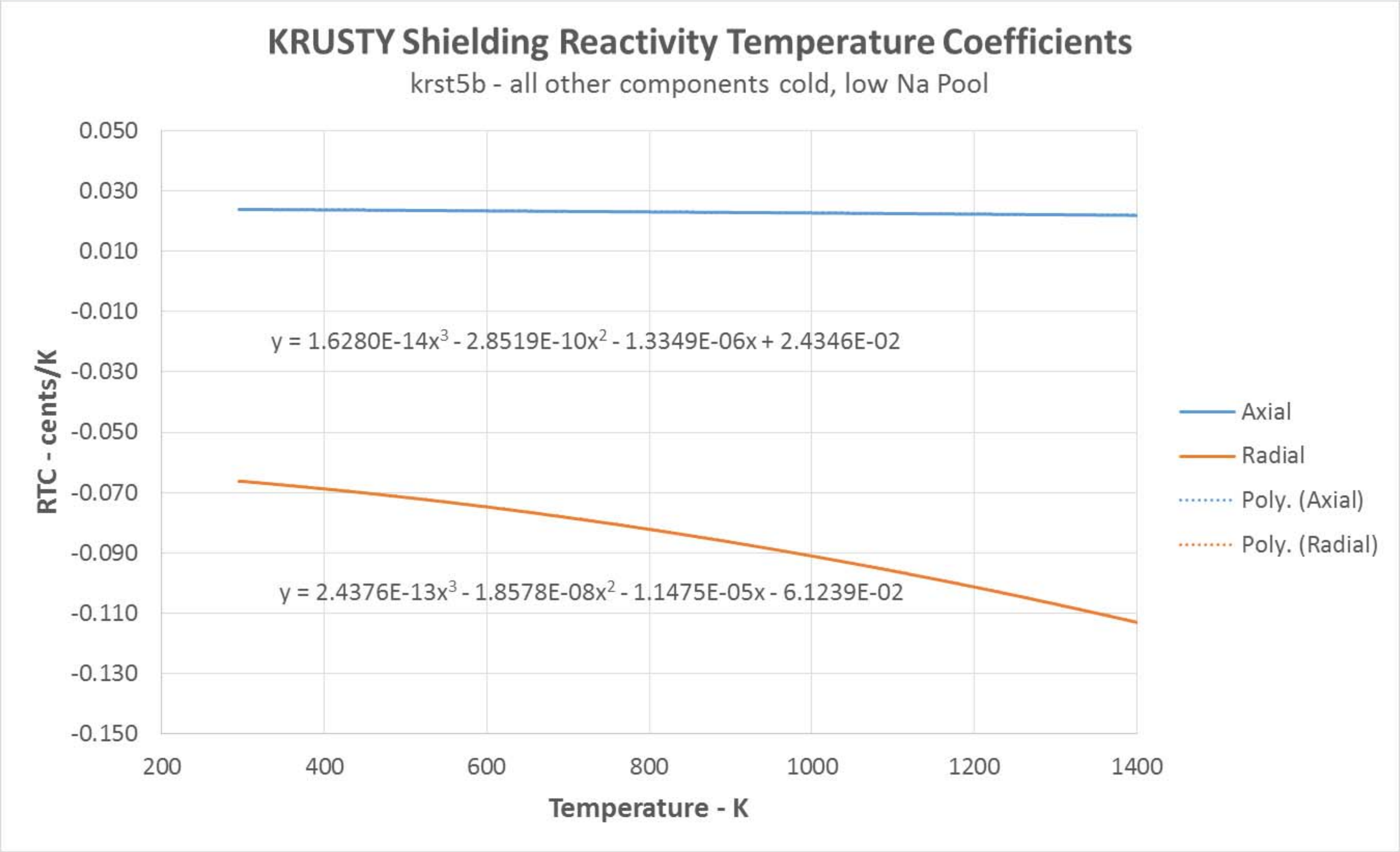
This is included just to visually demonstrate how much greater fuel feedback is than all of the other core mechanisms. Radial reflector and shielding not included because they heat very slowly (hours) and also to substantially lower steady-state temperatures.

Core-Can Reactivity Coefficient



Relatively large value RTC, but relatively little heating should occur.

Shielding Reactivity Coefficients



Relatively large value RTCs, but relatively almost no heating will occur.

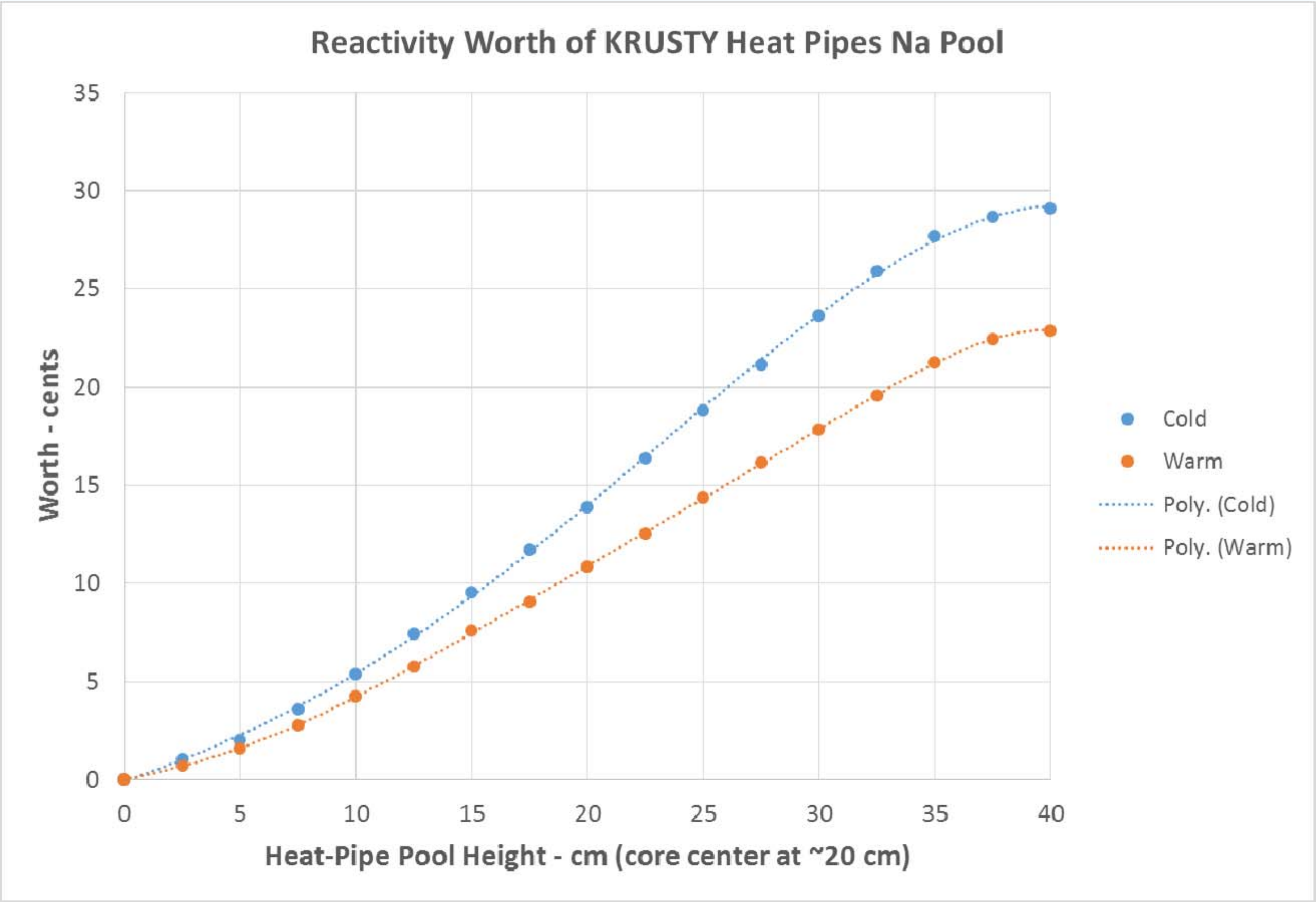
Summary of KRUSTY RTCs

Each of the RTCs is in polynomial form via a curve fit, which are used in FRINK, except for radial mli, for which a constant value was used based on the defect. The values at room temperature and operating temperature are shown. The values of the polynomials were slightly modified to reconcile the overall difference between the “inside-out defect” and the “RTC calcs with all other components cold”, so that the difference in worth between the two at operating temperature = 0. The calculated fuel RTC was left as is (unmodified) because is was heated with a cold balance of system in both cases.

	Operating Temp (K)	Reactivity Defect (cents)	Integral RTC at Operating Temp (cents/K)	RTC at Room Temp (cents/K)	Instantaneous RTC at Operating Temp (cents/K)
Fuel	1075	-157.9	-0.2029	-0.1195	-0.2825
Axial Reflector	413	-0.2	-0.0020	-0.0017	-0.0023
Heat Pipes	1051	-3.1	-0.0041	-0.0041	-0.0041
Core-Clamps	1045	-2.9	-0.0039	-0.0055	-0.0030
Radial MFI	806	-0.7	-0.0014	-0.0014	-0.0014
Vacuum Vessel	374	2.1	0.0274	0.0277	0.0270
Radial Reflector	311	0.2	0.0155	0.0161	0.0149
Platen Shielding	309	0.3	0.0239	0.0239	0.0239
Radial Shielding	297.2	0.0	-0.0663	-0.0663	-0.0663

The above calculations assume that the fuel expands freely (and brackets are pushed outward). This may or may not be correct, but is much easier to model. Overall, these local effects should not impact reactivity significantly (due to long neutron mfp), most important is that models conserve material mass (which they do). Another possible reactivity effect that is not modeled is separation of the 3 fuel segments.

Sodium Pool Level



Cold calculations assume Na density is the density of its melt/freeze temperature, i.e. it freezes with internal voids, as opposed to collapsing to 100% room temperature density. The above worth is for all 8 HP pools at same height.

The baseline HP design has a cold pool height of 17.5 cm, or 2.5 cm below core axial center. In this case the change in pool height with operation will at most be ~12 cents (i.e. if the entire pool is evaporated), or ~1.5 cents per individual HP. The pool height is a function of temperature (density), but even more-so a function of heat pipe power throughput, such that a good fraction of the pool is gone (flowing elsewhere in the HP) at full power (perhaps ~50% gone at 3 kWt core power)

Crude probability of "neutronic failure"

- "Neutronic failure" means KRUSTY does not achieve criticality at a desired temperature.
- My gut feel is that a conservative combined standard-deviation (1-sigma) of the MCNP calculated k-effs and defects is +/-$1
  - The vast majority of this is in the cold worth of the highly reflected BeO.
    - We will learn this early (the first cold crit), but if the models bias is severely high (say >$4) there's not much we can do about it. There's a few potential tricks up our sleeve for last minute reactivity boosts, ranging from 10s of cents to $1.
  - The guess of $1 is a major WAG - is tenuously gleaned from how changes in the Be and BeO SAB cross sections have impacted keff (moving from ENF6 and ENDF7.0 to ENDF7.1)
  - The calculated probabilities themselves are highly suspect, but the purpose of the calcs is to inform the target margin goals heading into the experiment.
    - The preferred amount of neutronic margin is a balance between the probability of success and the impact that excess reactivity has on nuclear safety and platen position/air-gap during operation.
- The table below shows percent chance of neutronic failure (not reaching criticality at given temperature) depending on the calculated margin (left col.) for a $1 uncertainty (assuming normal distribution, another dubious assumption). Current calculated margin = $1.62

Calc'd Margin	800 C	700 C	600 C	300 C	24 C
$0.00	50.0%	39.0%	29.5%	11.6%	5.1%
$0.50	30.9%	21.8%	14.9%	4.5%	1.6%
$1.00	15.9%	10.0%	6.2%	1.4%	0.4%
$1.50	6.7%	3.8%	2.1%	0.4%	0.1%
$2.00	2.3%	1.1%	0.6%	0.1%	0.0%

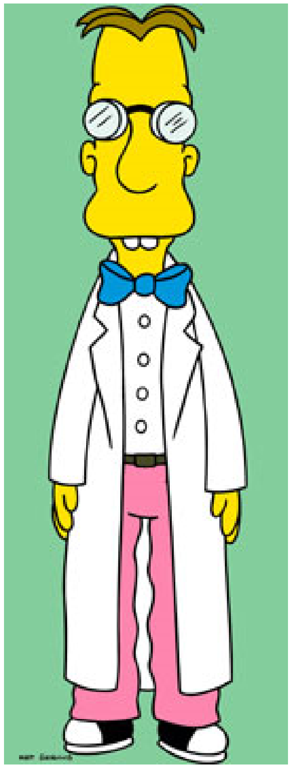
Reactivity aces in the hole?

- If the first critical shows a substantial positive modeling bias (i.e. experimental keff >>$1 lower than calculated), then options do exist to increase reactivity.

Modification	**cents added**
Add 1/8" BeO on top of full shim	11
Replace lower B4C platen shield with SS	23
Replace upper inner B4C plug shield in SS	5
Fill internal control rod space (full length), with…	
BeO rod	209
Mo rod	38
SS316 rod	49
SiO2 rod	71
B4C rod (99.99% B11)	138
B4C rod (95% B10) – reminder of control rod worth	-1125

- The control rod option utilizes the central space (pieces made to slide onto the central spool), but to add reactivity instead of subtract like the enriched B4C
  - Using this option (reflector/moderator in center) is not desirable because it is not flight prototypic, complicates feedback/modeling, and creates possible material issues (although we can likely wrap part in Mo mli).
  - Note: the bottom 10 cm of the rod (the current length of the central spindle) is only worth about 30% of the total (full length)
- The 1/8" BeO piece is desired for finer control of reactivity addition regardless
  - Note, it is worth ~30 cents on the platen stack, but only 11 cents as an extension to the top of the shim-stack

FRINK: Point Kinetics Equations



$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_i \lambda_i C_i(t) + S(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i(t)$$

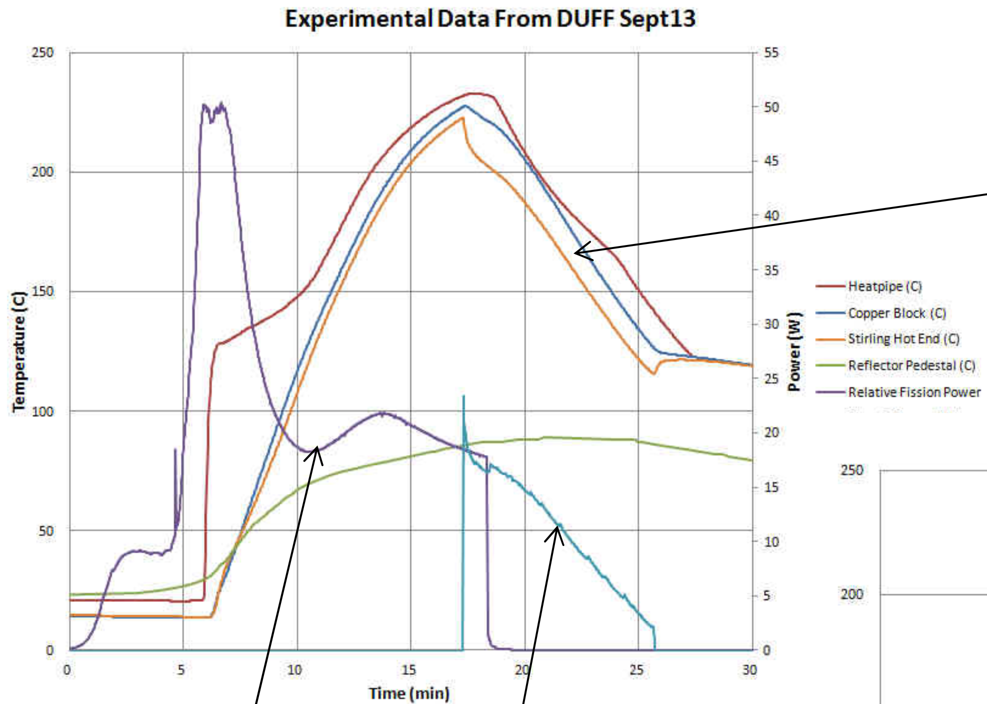
$$\rho(t) = K_0(t) + \sum_j \alpha_j(T_j)\,(T_j(t) - T_{0j})$$

$$P_{fis} = \left(\frac{1.6e-13 Q_{fis}}{\Lambda}\right)\left(\frac{\rho}{\nu}\right) n$$

FRINK incorporates betas (delayed groups) and alpha (reactivity feedback groups) differently than other codes

Sept 13th Results Compared with System Model

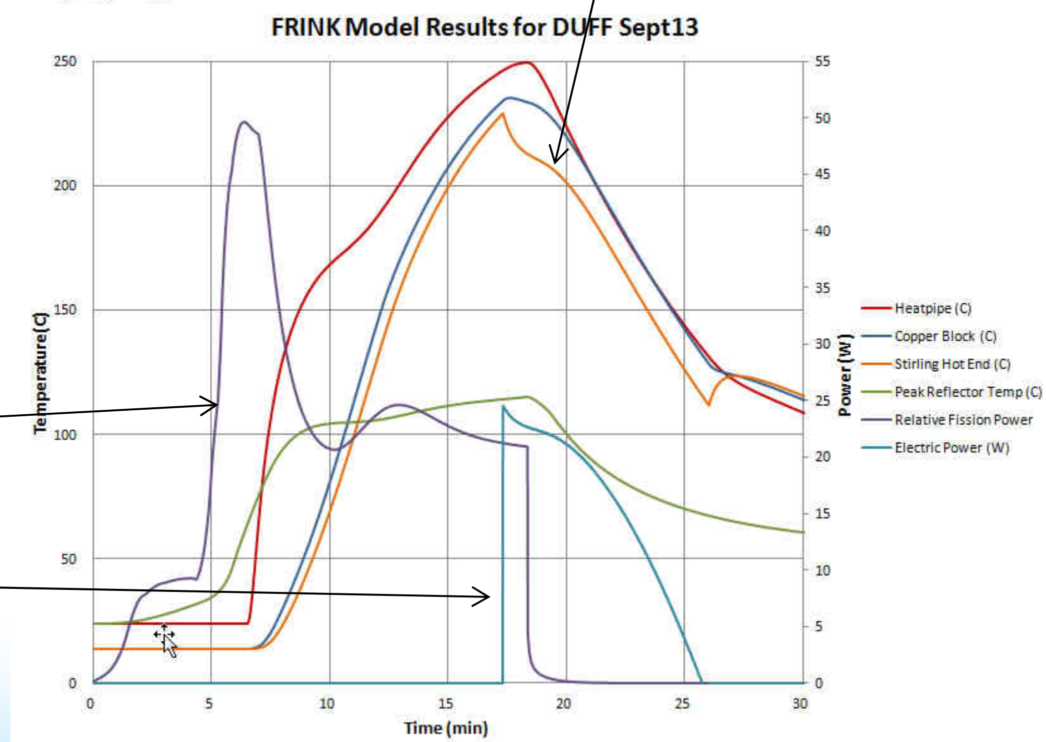
Slide 102



Power Conversion System Temperatures

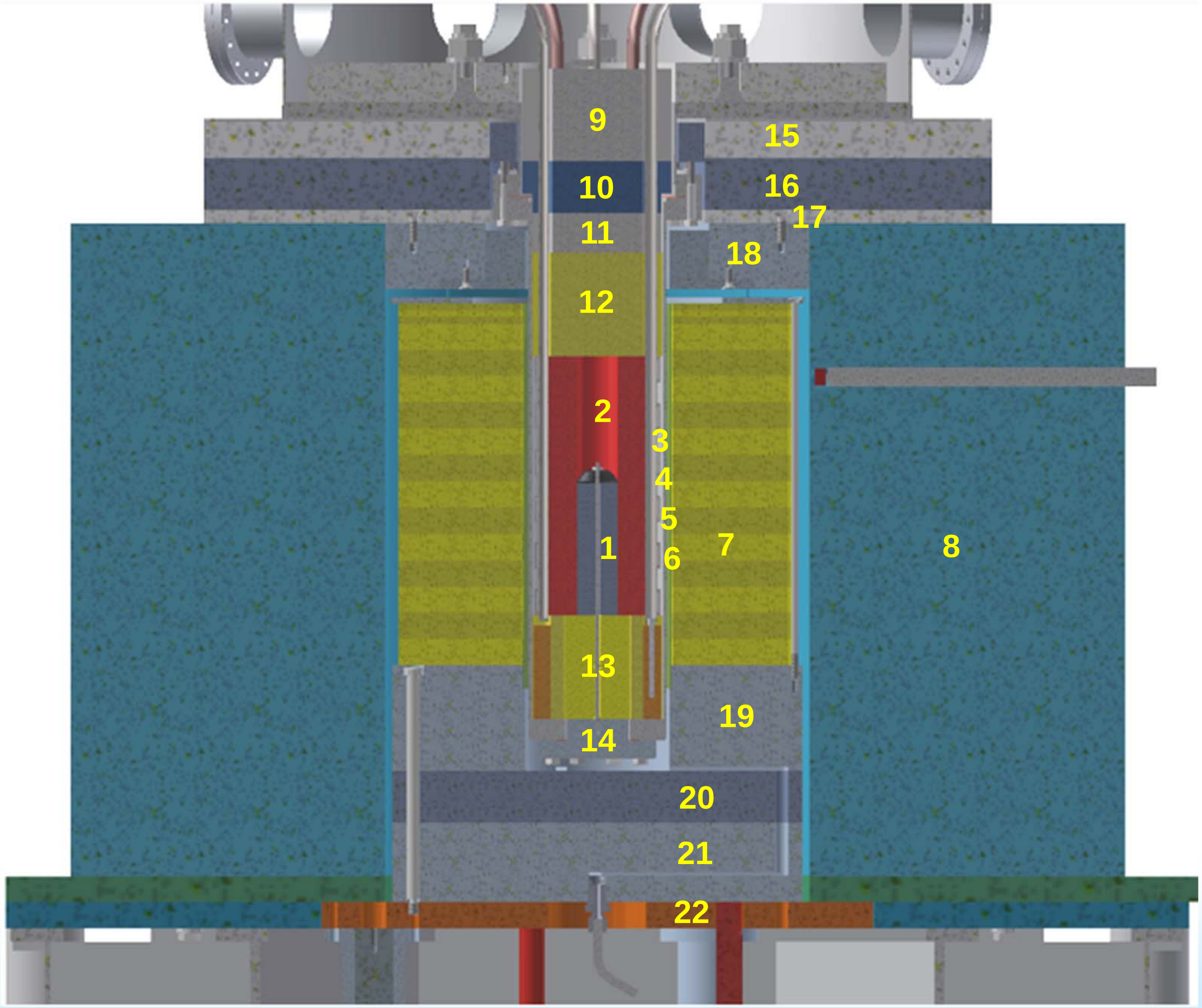
Reactor Thermal Power

Electric Power



KRUSTY FRINK Components

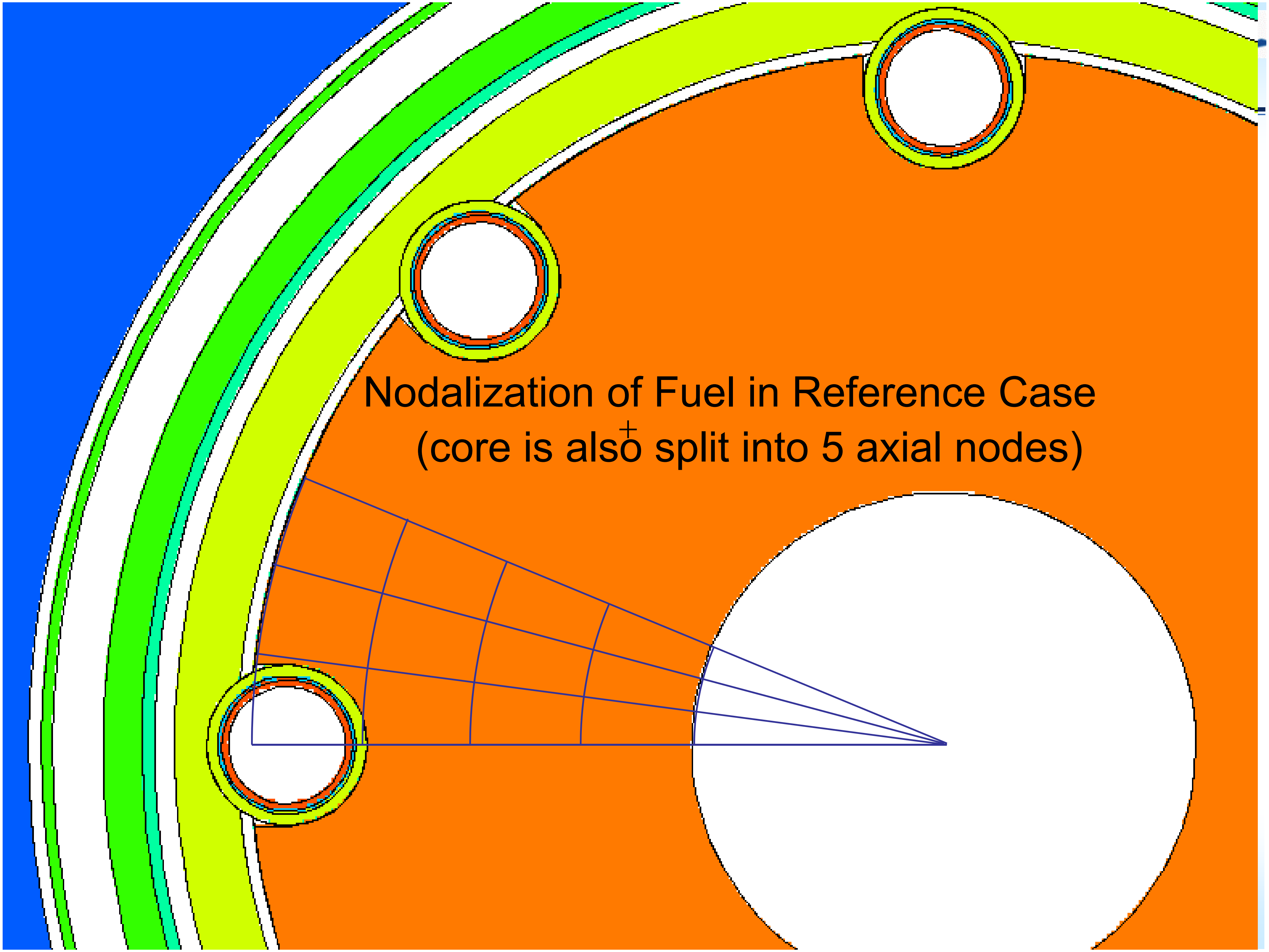
This is older design without shim-stack, but components are defined the same



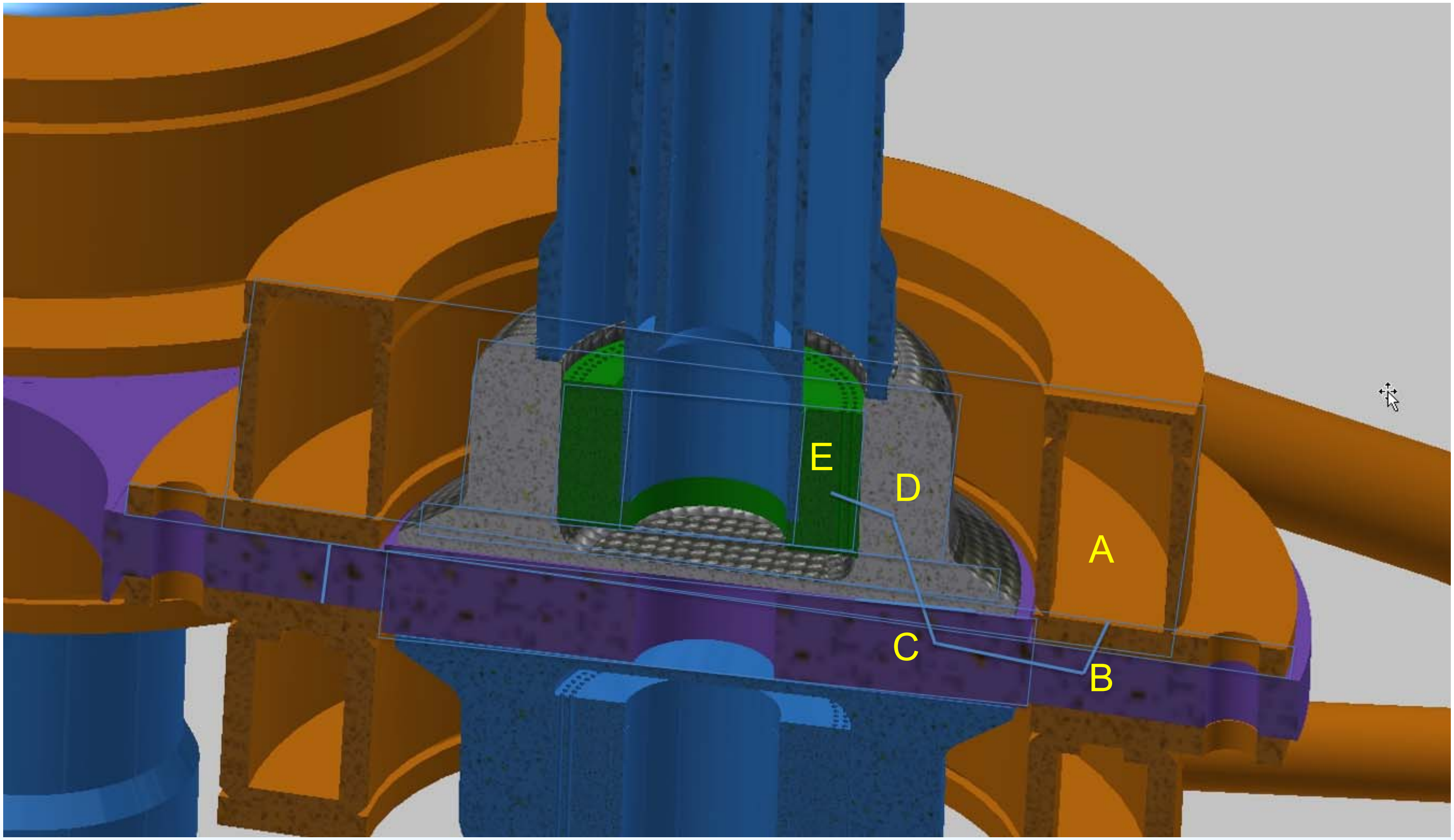
For the most part, the system is laid out on a r,theta,z mesh (except for heat pipes and nodes downstream)

Coupling of nodes is defined within FRINK input, as either.

- Conduction – full or impeded
- Air-gap
- Vacuum-gap
- Ambient air.


Nodalization of Fuel in Reference Case
(core is also split into 5 axial nodes)

Condensor/Stirling Nodes



FRINK Input: Materials and Coupling

```
c-------COMPONENT MATERIALS
Hay230    ! mat(0) ! heat pipe material
B4C       ! mat(1) ! safety rod material
UMo       ! mat(2) ! fuel material
Hay230    ! mat(3) ! clamp material
Astro     ! mat(4) ! mli material
SS316     ! mat(5) ! radial vessel material
SS316     ! mat(6) ! sleeve material
BeO       ! mat(7) ! radref material
SS316     ! mat(8) ! radshld material
SS316     ! mat(9) ! SS plug
B4C       ! mat(10)! B4C plug
SS316     ! mat(11)! SS internal shield
BeO       ! mat(12)! upper axref
BeO       ! mat(13)! lower axref
SS316     ! mat(14)! lower SS/ves
SS316     ! mat(15)! uppermost SS external shield
B4C       ! mat(16)! upper b4c external shield
SS316     ! mat(17)! upper SS external shield
SS316     ! mat(18)! upper wagon wheel
SS316     ! mat(19)! support wagon wheel
B4C       ! mat(20)! lower b4c shield
SS316     ! mat(21)! lower SS shield
Al        ! mat(22)! Platen
Na        ! mat(23)! HP coolant
c-------COMPONENT COUPLING (only "variable" ones, all others hardwired in code)
   0.800 ! qm0002 ! hp-fuel (1=solid/perfect,98=air gap, 99=vacuum gap)
   0.600 ! qm0003 ! hp-clamp (1=solid/perfect,98=air gap, 99=vacuum gap)
   0.500 ! qm0113 ! safety-axlo (1=solid/perfect,98=air gap, 99=vacuum gap)
   1.000 ! qm0212 ! fuel-mli-axhi (1=solid/perfect,98=air gap, 99=vacuum gap)
   1.000 ! qm0213 ! fuel-mli-axlo (1=solid/perfect,98=air gap, 99=vacuum gap)
   0.500 ! qm1314 ! axlo-ves (1=solid/perfect,98=air gap, 99=vacuum gap)
   0.500 ! qm1112 ! axhi-SS plug (1=solid/perfect,98=air gap, 99=vacuum gap)
   0.250 ! qm1011 ! SS plug-B4C plug (1=solid/perfect,98=air gap, 99=vacuum gap)
   1.000 ! qmstir ! Stirling collector to acceptor (1=solid/perfect,98=air gap, 99=vacuum gap
  297.0  ! tmamb  ! ambient room temp (K)
  287.0  ! tcold0 ! starting cold side temp (K)
   1.    ! tbound ! effective air boundary layer thick around shield (cm)
   1.    ! fudrmli! throughput of radial mli versus nominal model
   4.    ! fudx0mli! throughput of lower axial mli versus nominal model
   2.    ! fudx1mli! throughput of upper axial mli versus nominal model
```

FRINK Input: Design into

```
c------REACTOR DESIGN INFO-------------------------------------------
   25.00 ! zfuel  ! fuel length (cm)
    0.00 ! zsafe  ! height of safety rod (cm)
   10.08 ! zaxtop ! upper axial ref height (cm) - radref extent hardwired to 1/2 of this
   10.08 ! zaxbot ! lower axial reflector height (cm)
    2.50 ! zshtop ! upper inten. shield hght - add 1cm and split with zssup  (cm)
    3.87 ! zshbot ! lower ves floor/cap height (cm)
    1.27 ! zgaplo ! gap below ves, fully closed (cm)
    2.23 ! zveslo ! height low ves conduct path (ves floor) (cm)
    5.08 ! zb4bot ! bottom B4C shield on platen (cm)
    7.46 ! zssbot ! bottom SS shield on platen (cm)
    2.54 ! zplat  ! platen thick (cm)
    2.50 ! zssup  ! SS mount pice 1.27 cm but made larger to make node thicker for HP (cm)
    5.08 ! zb4up  ! top B4C (cm)
    7.89 ! zsstop ! top SS shield on stack, subtract 1cm to conserve height (cm)
   80.00 ! zhpex  ! length of HP above core (cm)
   0.546 ! r0(0)  ! hp IR (cm)
   0.635 ! r1(0)  ! hp OR (cm)
   0.000 ! r0(1)  ! safety OR (cm)
   1.960 ! r1(1)  ! safety OR (cm)
   2.000 ! r0(2)  ! fuel IR (cm)
   5.500 ! r1(2)  ! fuel OR (cm)
   5.772 ! r0(3)  ! clamp ir (cm)
   6.066 ! r1(3)  ! clamp or (cm)
   6.100 ! r0(4)  ! mli ir (cm)
   6.227 ! r1(4)  ! mli or (cm)
   6.350 ! r0(5)  ! ves ir (cm)
   6.655 ! r1(5)  ! ves or (cm)
   7.055 ! r0(6)  ! sleeve ir (cm)
   7.144 ! r1(6)  ! sleeve or (cm)
   7.244 ! r0(7)  ! radref ir (cm)
  19.209 ! r1(7)  ! radref or (cm)
  20.479 ! r1(8)  ! radial shield ir (cm)
  50.959 ! r1(8)  ! radial shield or (cm)
       8 ! nhp01  ! number of HPs in ring 1
       0 ! nhp02  ! number of HPs in ring 2
     5.2 ! ringh1 ! radius of HP ring 1
     0.0 ! ringh2 ! radius of HP ring 2
     50. ! arclam ! arc of HP-clamp contact
       6 ! nclamp ! number of clamp rings
    2.54 ! zclamp ! clamp height (cm)
```

FRINK Input: Nodalization

```
c------COMPUTATIONAL PARAMETERS------------------------------------------
16        ! nslice  ! symmetry slice (theta 360/n), must leave at least 1/2 HP
3         ! ntheta  ! # aximuthal nodes in fuel (HPs fit within)
1         ! nr(0)   ! # radial nodes HP (0 to n)
1         ! nr(1)   ! # radial nodes safety rod (1 to n)
4         ! nr(2)   ! # radial nodes fuel meat (1 to n)
1         ! nr(3)   ! # radial nodes clamp (0 or 1)
1         ! nr(4)   ! # radial nodes multi-foil (0 or 1)
1         ! nr(5)   ! # radial nodes vessel (0 or 1)
1         ! nr(6)   ! # radial nodes sleeve (0 or 1)
1         ! nr(7)   ! # radial nodes radref (0 or n)
1         ! nr(8)   ! # radial nodes shield (0 or n)
6         ! nzfuel  ! 3 or 6 # axial nodes fuel meat (1 to n)
2         ! nzaxref ! # axial nodes axref (0 to n - must be even)
4         ! nzshlo  ! # axial nodes below axref (0 to n) - ves, then move with RR
4         ! nzshhi  ! # axial nodes above aref (0 to n) - with fuel
3         ! nzhpex  ! # axial nodes heat pipe above core (adibatic+condensor)
5         ! nzstir  ! # nodes cond/stir hot side (not really axial, but arrayed that way)
1         ! ipre   ! 1) start with steady state precursor concentrations and decay power
0.5       ! theta  ! crank nicholson parameter
1.0e-9    ! dtmin  ! minimum dtime
1.0e-6    ! dtbog1 ! if t falls below this, increaase much faster
1.0e-5    ! dtbog2 ! if t falls below this, increaase faster
1.0e-4    ! dtbog3 ! if t falls below this, increaase a bit faster
1.0e-3    ! dtbog4 ! if t falls below this, increaase a bit faster
1.0e-2    ! dtbog5 ! if t falls below this, increaase a bit faster
5.0e-2    ! dt     ! initial dtime
5.0e-2    ! dtmax  ! maximum dtime
.0005     ! epct   ! .00001 error tolerance per step, sets dt
10.0      ! tprt   ! (.953) print interval
```

FRINK Input: Power Fractions and Feedback

```
c-------POWER and FEEDBACK DATA
22        ! ncomp  ! number of components (+ zero case)
0.00054 !pfrac(0)        fraction power heat pipes
0.00000 !pfrac(1)        fraction power safety rod
0.93902 !pfrac(2)        fraction power fuel
0.00080 !pfrac(3)        fraction power clamps
0.00010 !pfrac(4)        fraction power multifoil
0.00123 !pfrac(5)        fraction power radial vessel
0.00032 !pfrac(6)        fraction power radref sleeve
0.01626 !pfrac(7)        fraction power radref
0.02864 !pfrac(8)        fraction power radial shield
0.00011 !pfrac(9)        fraction power upper in ves ss plug
0.00024 !pfrac(10)       fraction power upper in ves B4C
0.00005 !pfrac(11)       fraction power upper in ves shield
0.00063 !pfrac(12)       fraction power upper axref
0.00082 !pfrac(13)       fraction power lower axref
0.00019 !pfrac(14)       fraction power lower SS/ves
0.00051 !pfrac(15)       fraction power uppermost external ss shield
0.00258 !pfrac(16)       fraction power upper external B4C shield
0.00037 !pfrac(17)       fraction power upper external ss shield
0.00237 !pfrac(18)       fraction power upper wagon wheel
0.00350 !pfrac(19)       fraction power support wagon wheel
0.00144 !pfrac(20)       fraction power lower B4C shield
0.00027 !pfrac(21)       fraction power lower ss shield
0.00001 !pfrac(22)       fraction power platen
 6.0797E-13,-1.6180E-09, 1.3504E-06,-4.4031E-03 ! rtc(0)  ! rtc of heat pipes
0.,0.,0.,0.                                     ! rtc(1)  ! rtc of safety rod
-1.6951E-11, 5.0121E-08,-1.4888E-04,-7.9756E-02 ! rtc(2)  ! rtc of fuel
 5.6058E-13,-2.4640E-09, 4.5602E-06,-6.5938E-03 ! rtc(3)  ! rtc of clamps
0.,0.,0.,-.00137                                ! rtc(4)  ! rtc of multifoil
-1.2485E-12, 5.2741E-09,-7.8830E-06, 2.9629E-02 ! rtc(5)  ! rtc of radial vessel
0.,0.,0.,0.                                     ! rtc(6)  ! rtc of radref sleeve
 1.9502E-11,-4.0660E-08,-1.2943E-05, 2.2913E-02 ! rtc(7)  ! rtc of radref
 2.4376E-13,-1.8578E-08,-1.1475E-05,-6.1239E-02 ! rtc(8)  ! rtc of radial shield
0.,0.,0.,0.                                     ! rtc(9)  ! rtc of upper in ves ss plug
0.,0.,0.,0.                                     ! rtc(10) ! rtc of upper in ves B4C plug
0.,0.,0.,0.                                     ! rtc(11) ! rtc of upper in ves shield
-9.2745E-13, 2.5692E-09,-2.7700E-06,-2.5253E-04 ! rtc(12) ! rtc of upper axref
-9.2745E-13, 2.5692E-09,-2.7700E-06,-2.5253E-04 ! rtc(13) ! rtc of lower axref
0.,0.,0.,0.                                     ! rtc(14) ! rtc of lower SS/ves
0.,0.,0.,0.                                     ! rtc(15) ! rtc of uppermost external ss shie
0.,0.,0.,0.                                     ! rtc(16) ! rtc of upper external B4C shield
0.,0.,0.,0.                                     ! rtc(17) ! rtc of upper external ss shield
0.,0.,0.,0.                                     ! rtc(18) ! rtc of upper wagon wheel
 8.1400E-15,-1.4260E-10,-6.6745E-07, 1.2173E-02 ! rtc(19) ! rtc of support wagon wheel
 1.6280E-15,-2.8519E-11,-1.3349E-07, 2.4346E-03 ! rtc(20) ! rtc of lower B4C shield
 6.5120E-15,-1.1408E-10,-5.3396E-07, 9.7384E-03 ! rtc(21) ! rtc of lower ss shield
0.,0.,0.,0.                                     ! rtc(22) ! rtc of platen
```

FRINK Input: Kinetic/Delay Info

```
c-------DECAY POWER DATA-(set up energy bins with different release rates)----
17       ! ndc  ! number of decay power bins, tdc(i),qdc0(i) decay fractions below
0.00E+00        ,       6.508E-02
1.00E-01        ,       6.425E-02
3.16E-01        ,       6.277E-02
1.00E+00        ,       5.971E-02
3.16E+00        ,       5.462E-02
1.00E+01        ,       4.767E-02
3.16E+01        ,       3.964E-02
1.00E+02        ,       3.157E-02
3.16E+02        ,       2.474E-02
1.00E+03        ,       1.911E-02
3.16E+03        ,       1.365E-02
1.00E+04        ,       9.370E-03
3.16E+04        ,       6.500E-03
1.00E+05        ,       4.510E-03
1.00E+06        ,       2.220E-03
1.00E+07        ,       6.934E-04
1.00E+08        ,       9.141E-05
1.00E+10        ,       1.143E-06
c-------KINETIC/DELAYED DATA---------------------------------------------
5.5E-8   ! alamda ! prompt fission lifetime (3.4e-7, or 5.5e-8 if geometric delay)
0.95     ! spect  ! delay groups linear scaled between 0) thermal and 1) fast
0.       ! fpct(1)! th232 fraction of fissions
0.       ! fpct(2)! u233 fraction of fissions
0.99     ! fpct(3)! u235 fraction of fissions
0.01     ! fpct(4)! u238 fraction of fissions
0.       ! fpct(5)! pu239 fraction of fissions
0.       ! fpct(6)! pu240 fraction of fissions
0.       ! fpct(7)! pu241 fraction of fissions
0.       ! fpct(8)! pu242 fraction of fissions
10       ! ndelay ! number of geometric delayed groups
3.37e+5  ! la(?)  ! time constant of delayed group
.04454   ! be(?)  ! beta effective of delayed group
5.33e+4
.01741
2.36e+4
.00518
1.49e+4
.00491
9.38e+3
.00475
5.94e+3
.00438
3.77e+3
.00358
2.40e+3
.00233
1.49e+3
.00117
8.55e+2
.00019
```

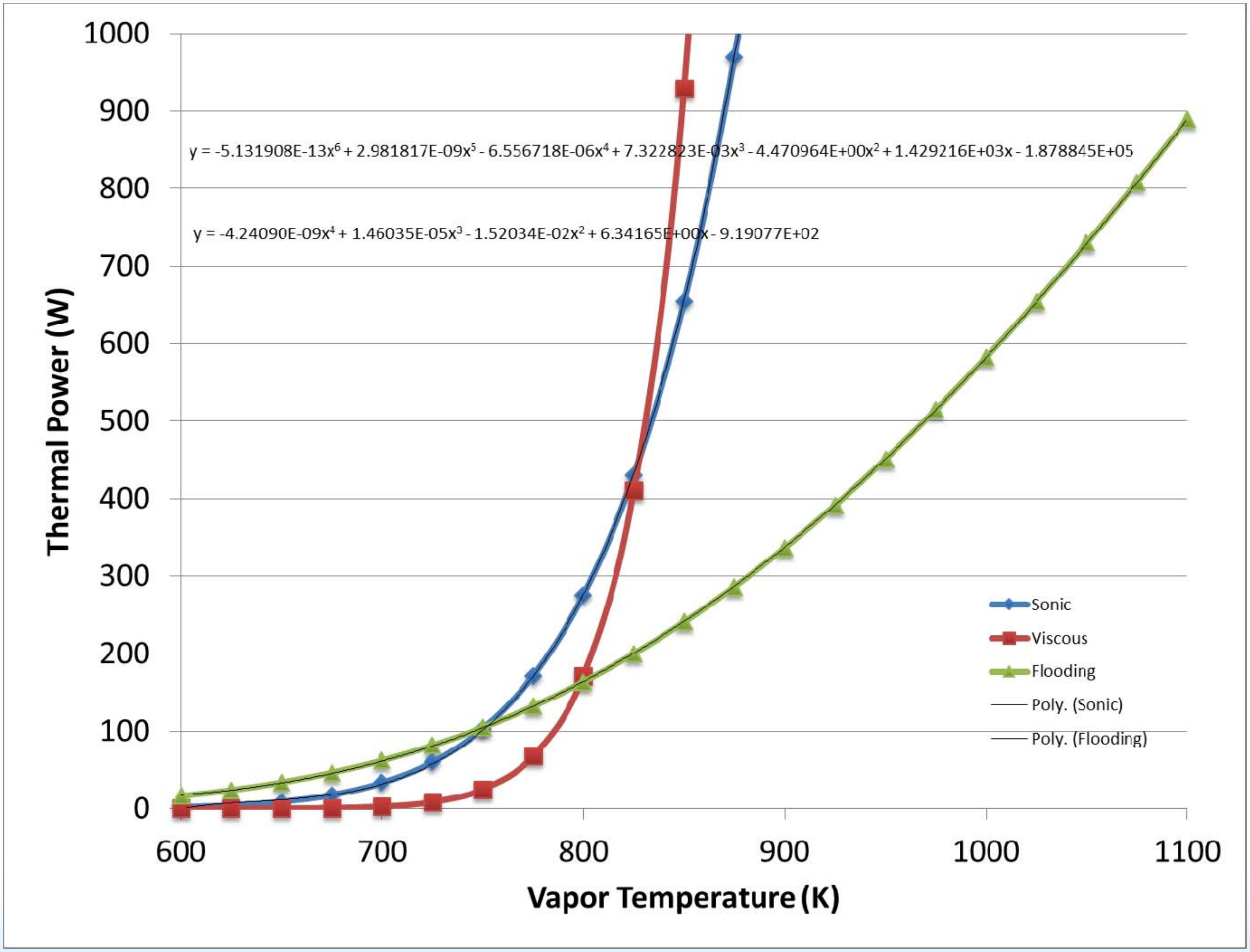
Rene Simulator in FRINK

- Added a feature to FRINK that controls reactivity vs
  - Fuel temperature
    - During test will be based on the reading from thermocouples, or averages of thermocouples.
      - Perhaps 2 metrics – peak core temp and average core temp
  - Power
    - Power will be a function of one or more count rates
    - During first powered test, the power will be calculated based on temperature increase as a function of neutron count rate.
      - First test proposes an ~20 cent free run, which can serve the benchmark to arrive at the power/count rate ratio.
    - We might get some feeling for power versus count rate from zero power criticals
      - But that would rely too much on model accuracy, in particular coupling of the source – Q=mCp is much more accurate.
    - A final benchmark of power will be when we operate at steady-state with a “known” Stirling engine power draw (plus other thermal leakage)
  - Slope of power
    - This “requirement” probably not needed, but adds a level of conservatism
      - I.e. only add reactivity when the slope of power is negative, which means you have to wait until at “free run” fully turns around before adding again.
- Example case uses the following
  - Move table up .006” if all conditions are met…
    - Peak fuel temp <1123 K (850)
    - Average fuel temp < 1073 K (800 C)
    - Fission power < 3 kW
    - Slope of power negative
  - 0.006” corresponds to about 2 cents of reactivity.

FRINK Input: Transient Definition

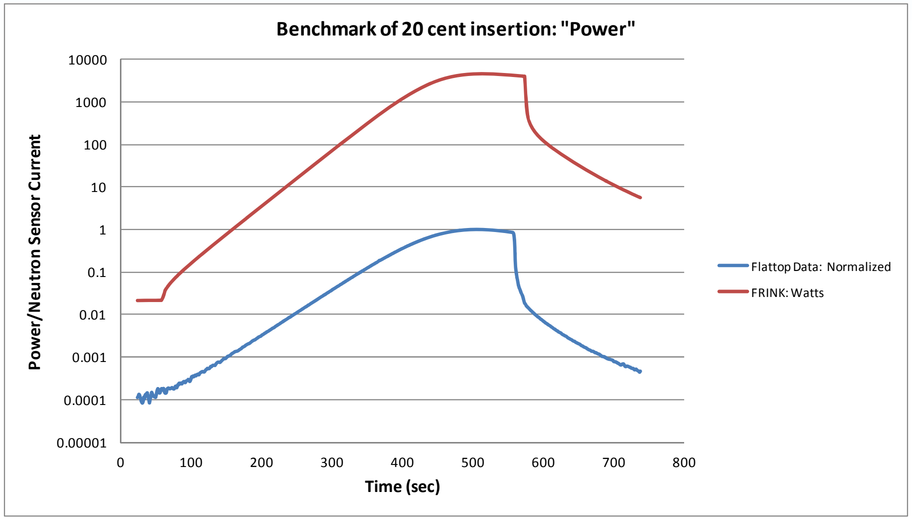
```
c------POWER, REACTIVITY and SOUCE INFO---------------------------------
-10.     ! tstart  ! start time (s)
21600.0 ! tstop   ! transient end time
1        ! ibriggs ! 1) stirling run  0) nope
923.     ! tmstart ! Start Stir when HH temp (if=0 use nstroke events below)
573.     ! tmshut  ! Shutdown Stir when HH temp (unless nstroke used)
86400.   ! tishut  ! Shutdown Stir at this time (unless nstroke used)
0.       ! hpsuper ! Force to keep HP off until this temperature (K)
0.       ! hpkick  ! Force to keep HP off until this time
1000.    ! s0      ! neutron souce, set low for single event (n/s)
3        ! irtype  ! 0) dk, 1) $, 2) platen pos, 3) rene (uses nreact in dollars, then )
0.0069   ! betaef ! .0069 beta effective of delayed fission (if=0 use material yield value)
3.6644E-07,1.7542E-06,-4.5126E-04,-5.9120E-03,0.0149 ! Rreactivity (keff-1) as fn of platen (
-7.9154E+04,-1.1907E+04,-9.3010E+02,-1.2829E+02,2.1675 ! Platen (cm) as fn of reactivity (kef
-1.0     ! ri0     ! initial reactivity (keff - 1)  or platen position
2900.    ! pobump  ! Rene don't bump reactivity if P>pobump (slope must be neg too)
1073.    ! tebump  ! Rene don't bump reactivity if T>tebump
0.0152   ! bump    ! Rene size of in cm moved (this is 0.006")
3.       ! tbump   ! Rene seconds over which bump added
18000.0 ! tscram  ! Hardwired scram time - overrides other controls
1        ! nreact   ! # reactivity events (t1, t2, $inserted or platen position)
 -10., -0.1, 1.14
0        ! nstroke  ! number of Stirling events (time, stroke fraction)
0.       ! power  ! initial power (kW)
```

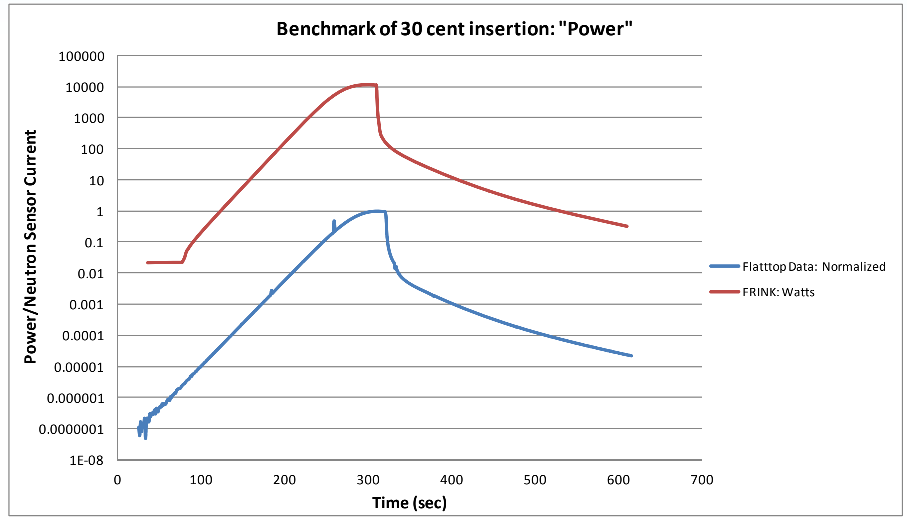
Sodium HP Model

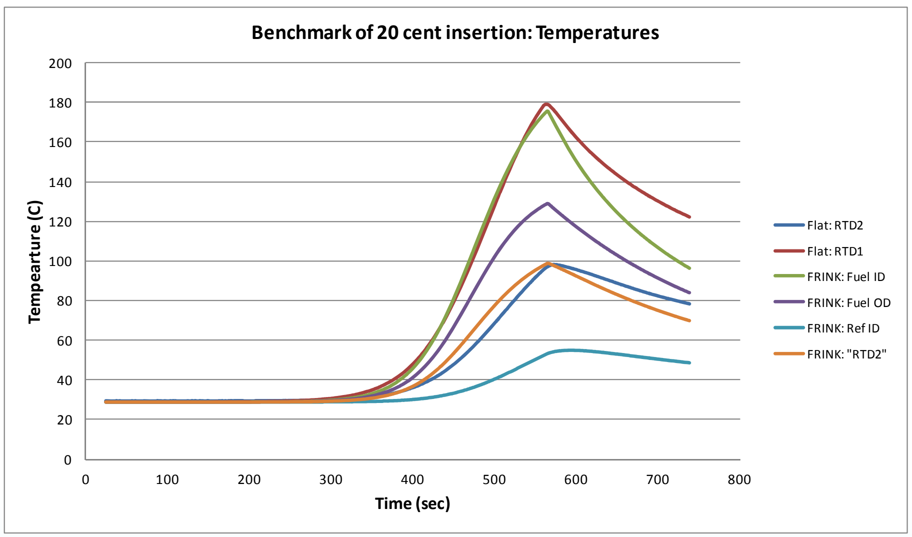


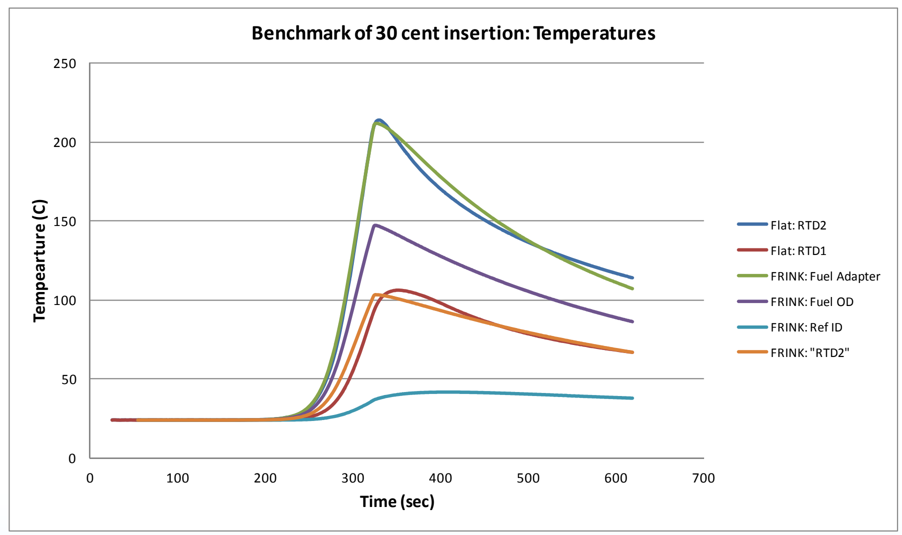
Plot From Gibson

Flattop Free Runs









The initial reactor test of KRUSTY will be a simple free run, where a set amount of reactivity is inserted and the system passively responds via temperature feedback. Note that FRINK was first benchmarked to various Flattop free runs, and as result it predicted the DUFF test extremely well (not a surprise since DUFF was essentially Flattop with a SS/H2O heat pipe inserted.

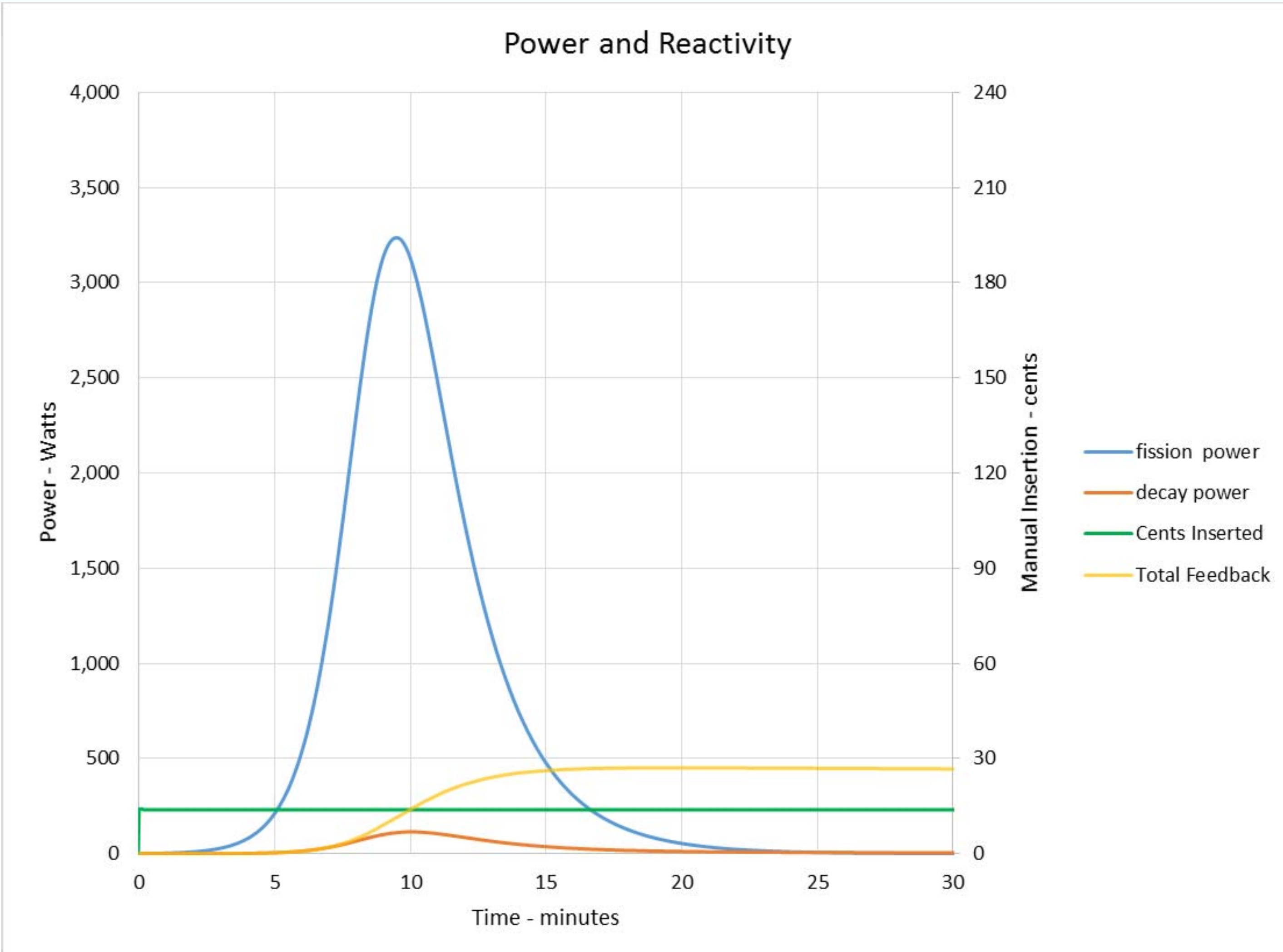
Flattop Free Runs vs KRUSTY predict

Flattop	Actual insertion (cents)	Peak power (kWt)	Max. ave. fuel temp (C)	Ave. temp at power turn (C)	Ave. temp at rho=0 (C)
~10 cent	11.7	1.48	113.1	85.1	93.6
~20 cent	19.0	3.88	153.3	114.6	137
~30 cent	31.3	11.80	182.4	145.2	181.9
KRUSTY					
~10 cent	11.7	2.25	181.7	99.2	111.9
~20 cent	19.0	6.18	266.4	130.9	161.9
~30 cent	31.3	19.15	393.9	165.1	238.6

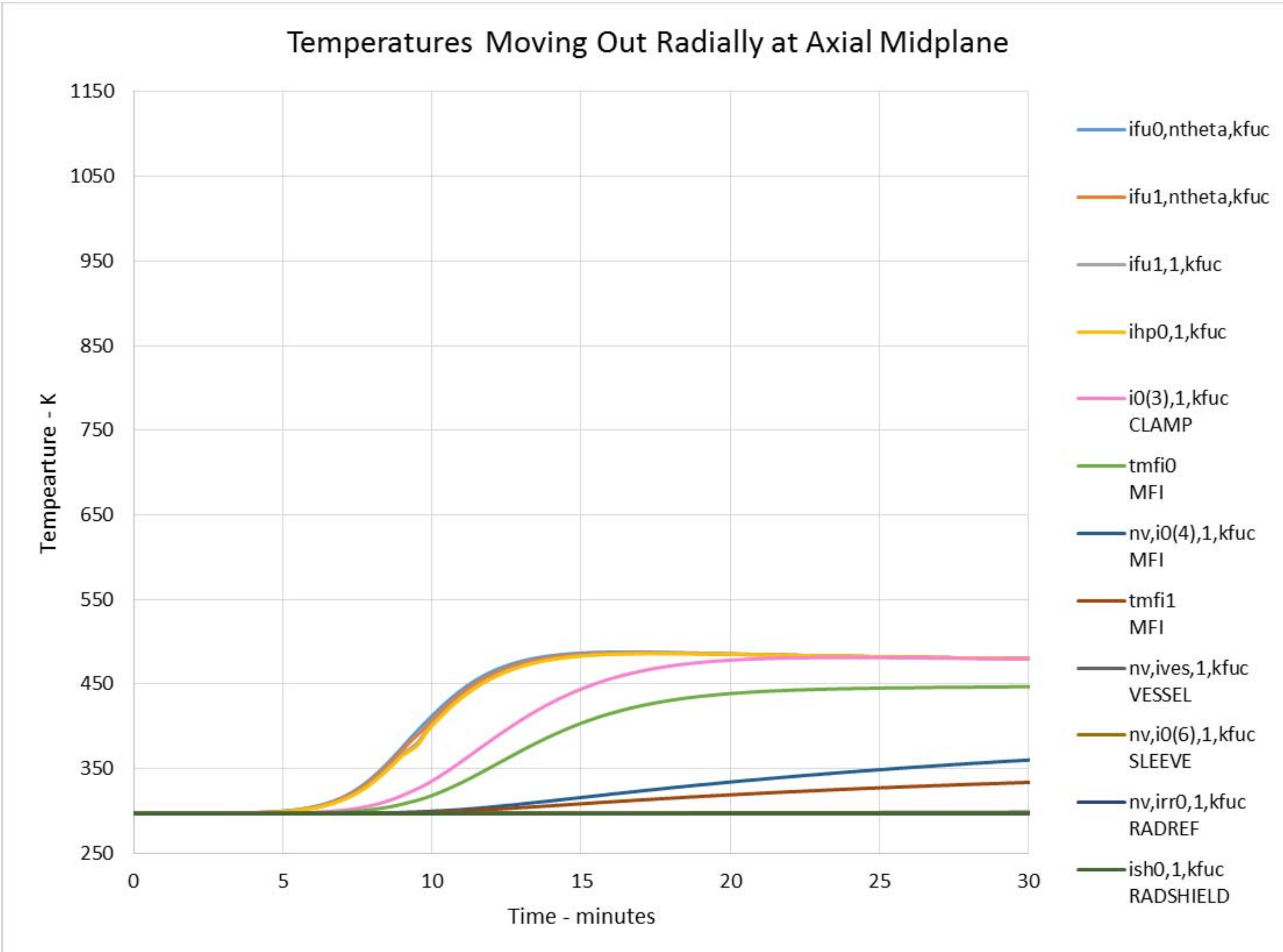
This table shows the FRINK results for 3 actual Flattop free runs, loosely labeled 10, 20 and 30 cent insertions, but the slope of the power indicated slightly different numbers (so those are used).

KRUSTY is predicted to reach higher power for a given free run insertion, because of higher thermal inertia (takes longer to heat up) and lower feedback coefficient (better reflection, so core leakage hurts less). Flattop maximum temperatures also lower because core is poorly insulated, while KRUSTY is well insulated.

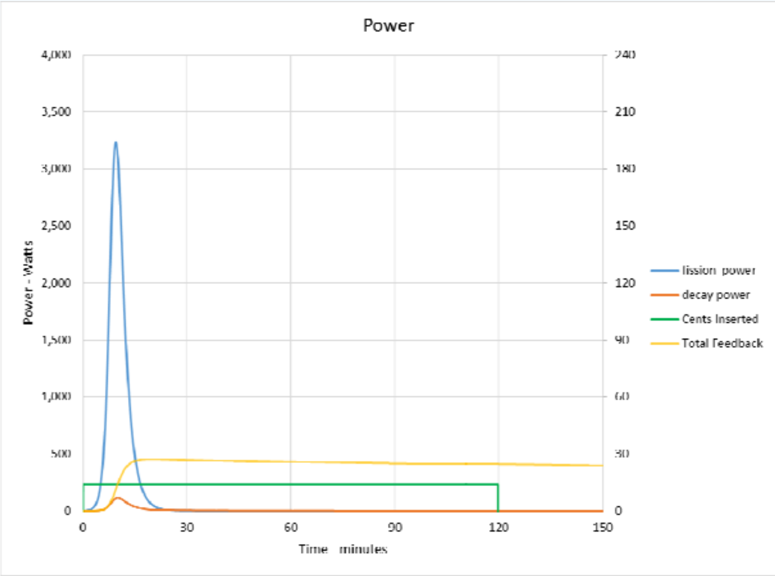
KRUSTY 15 cent free run – 1st 30 min.

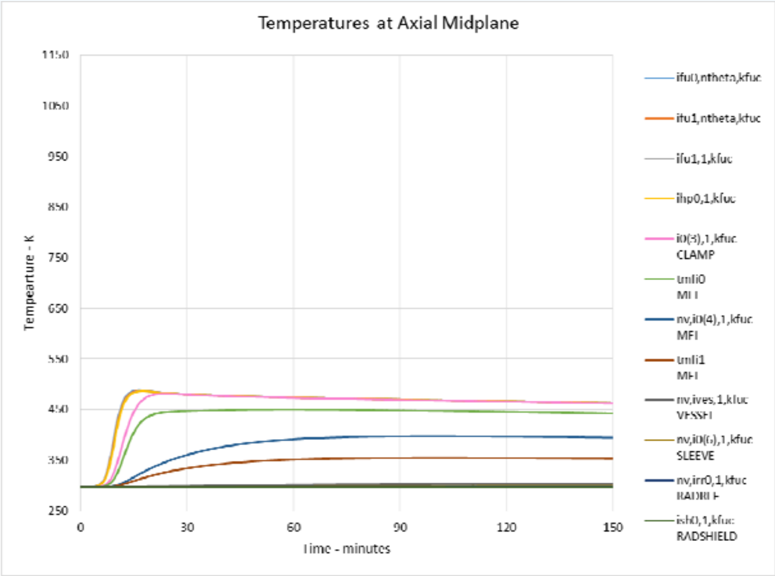


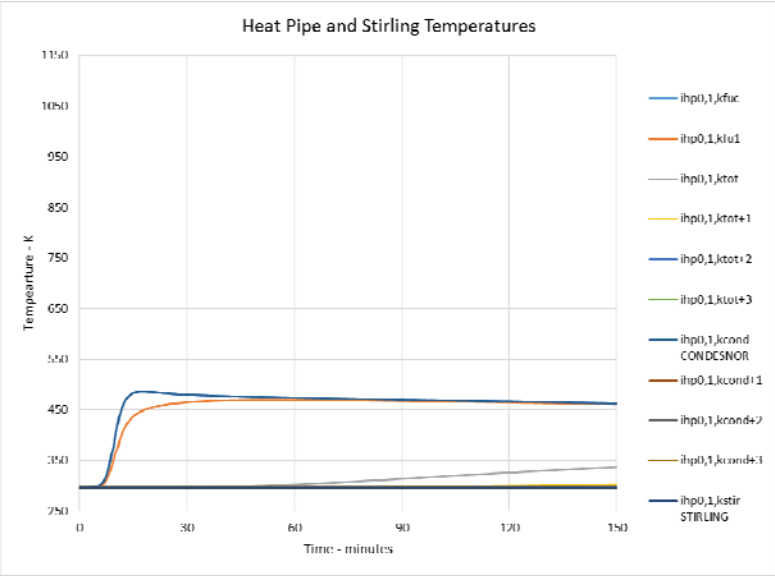
KRUSTY 15 cent free run – 1st 30 min.

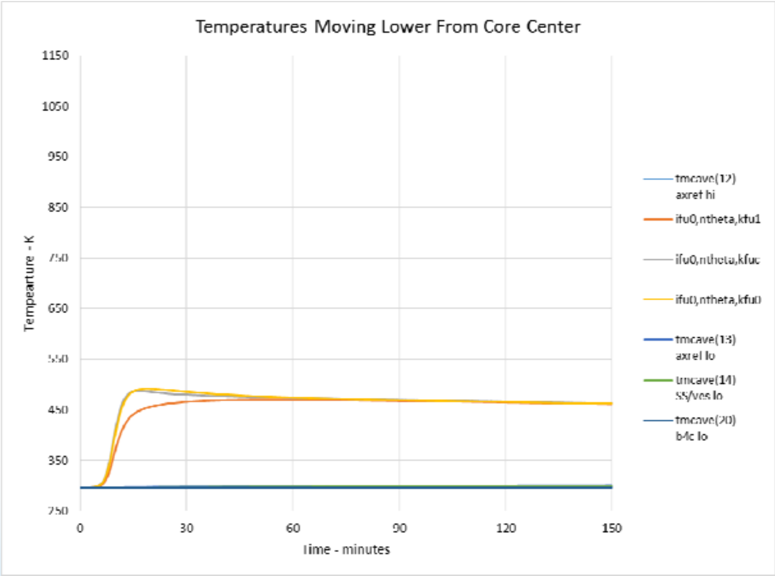


KRUSTY 15 cent free run
2 hours them scram



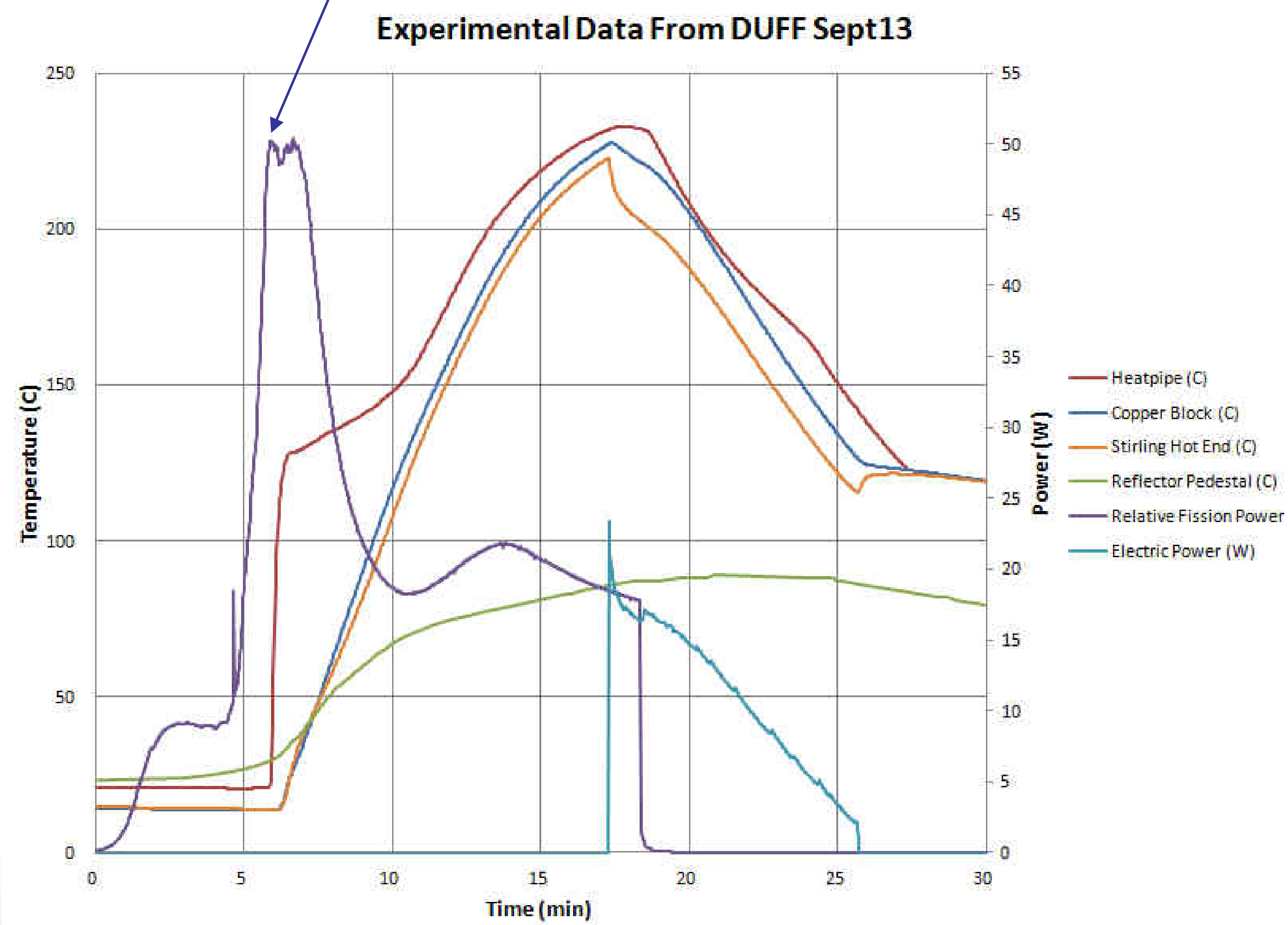






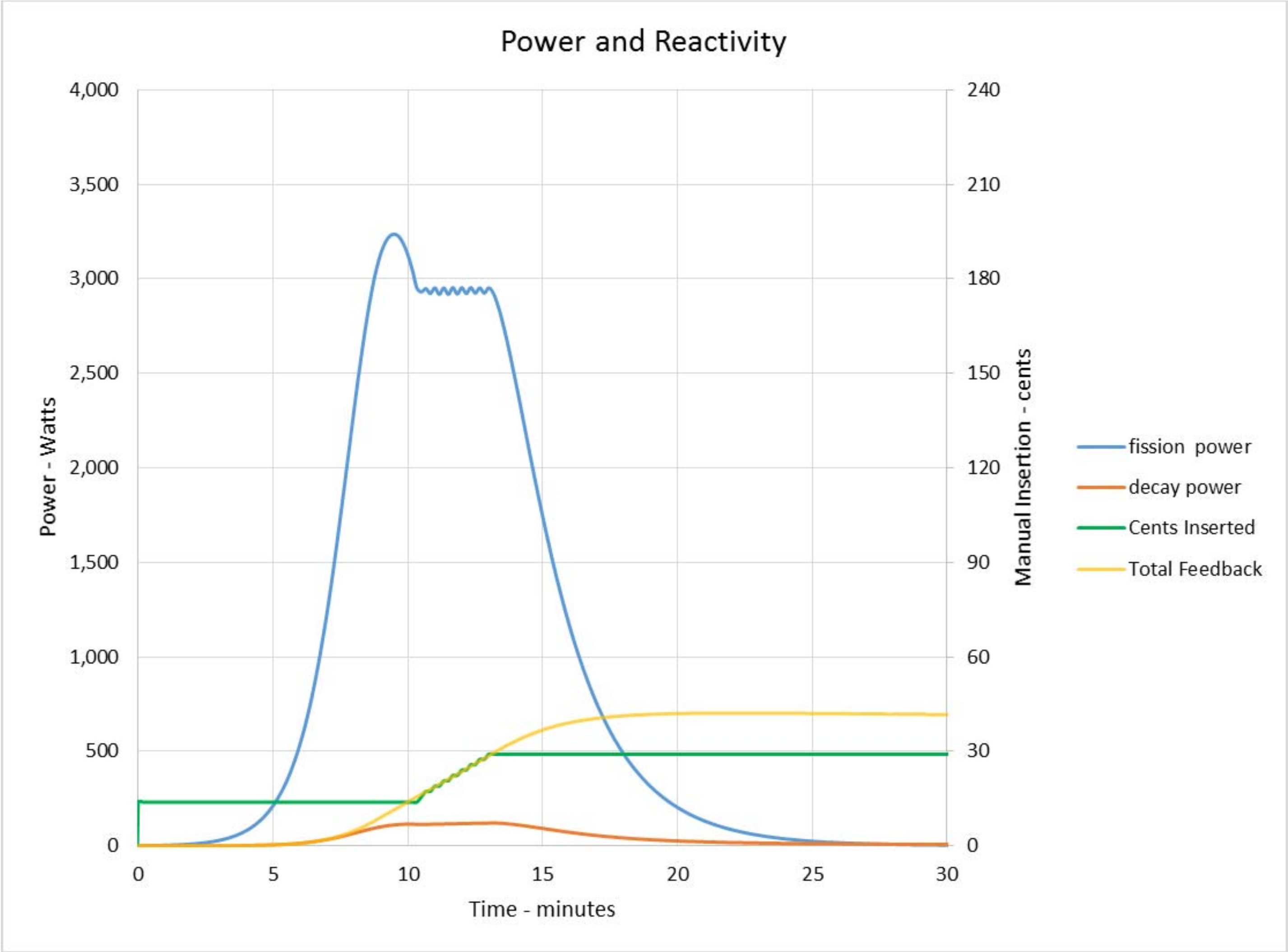
Now continue to higher insertions, similar to what was done for DUFF

Bounds adds reactivity to keep power at ~10 kWt until he runs out of juice.

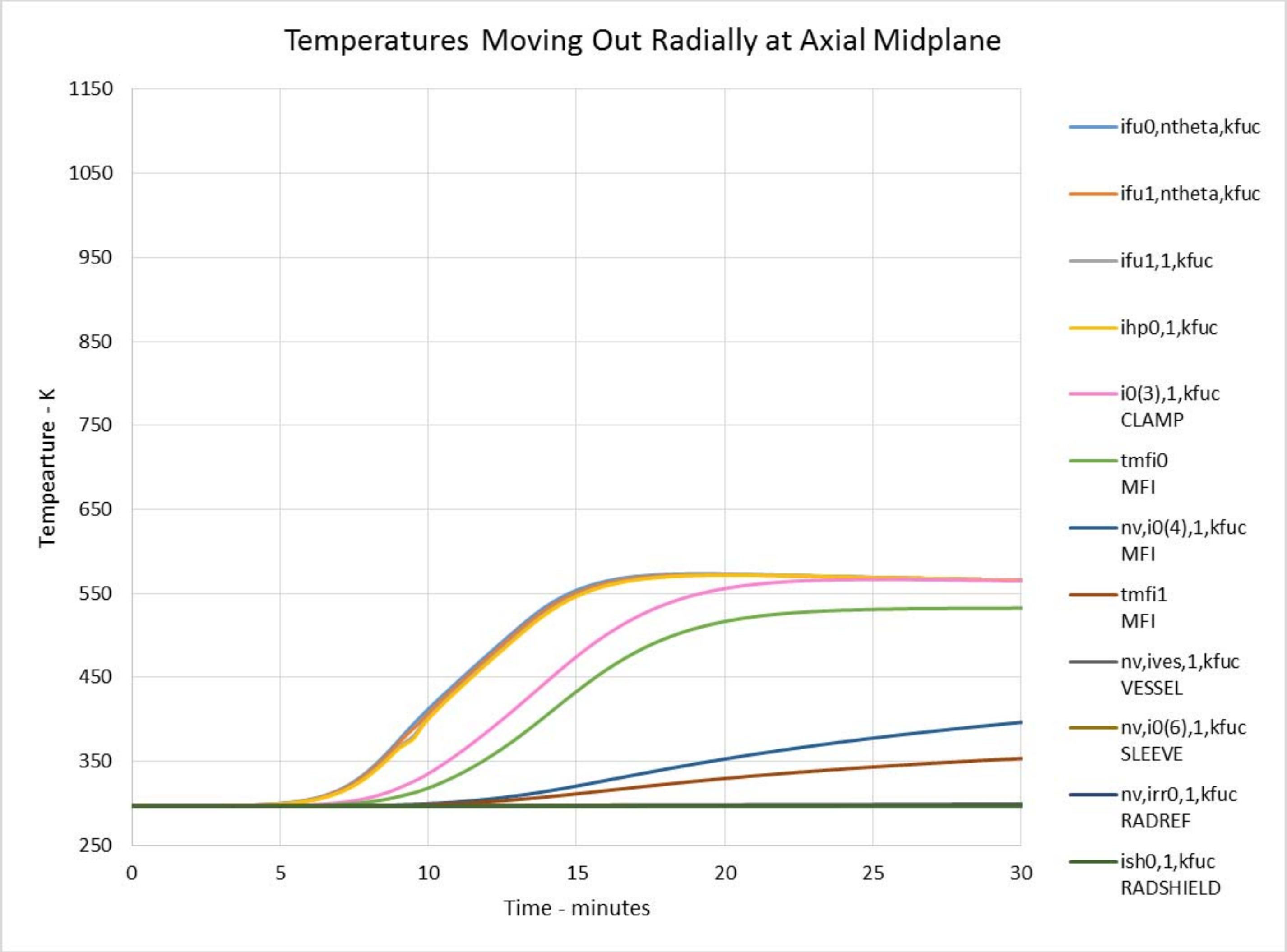


After initial insertion, continuously add reactivity to maintain power.

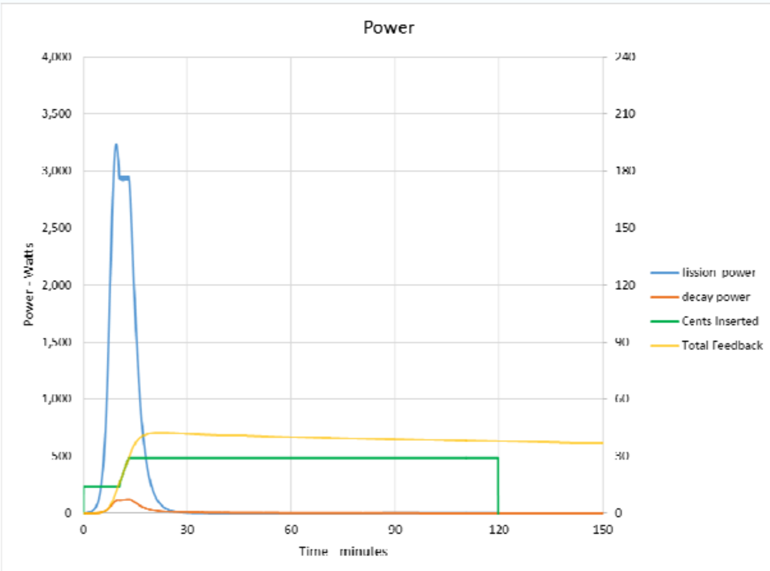
KRUSTY 30 cent run – 1st 30 min.

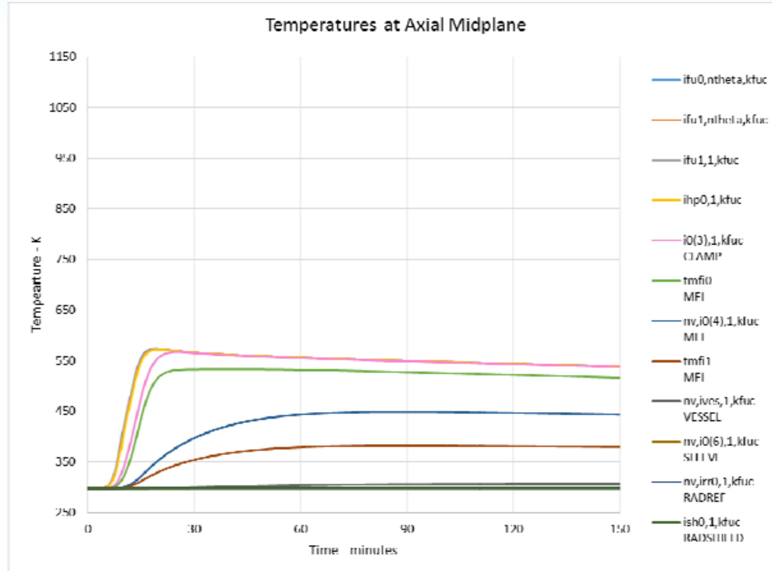


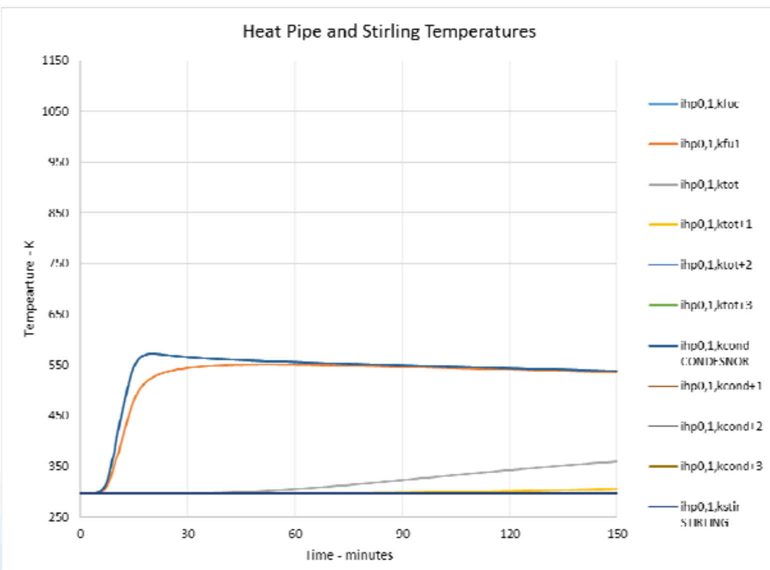
KRUSTY 30 cent run – 1st 30 min.

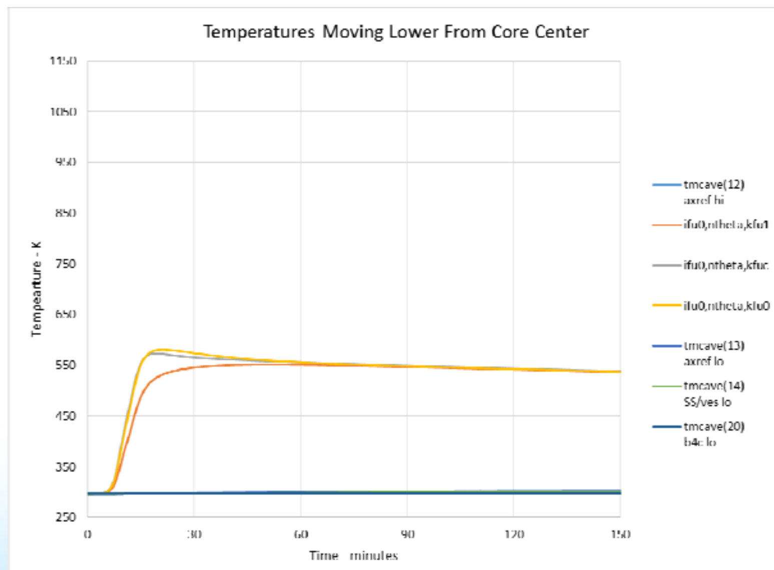


KRUSTY 30 cent run
2 hours them scram

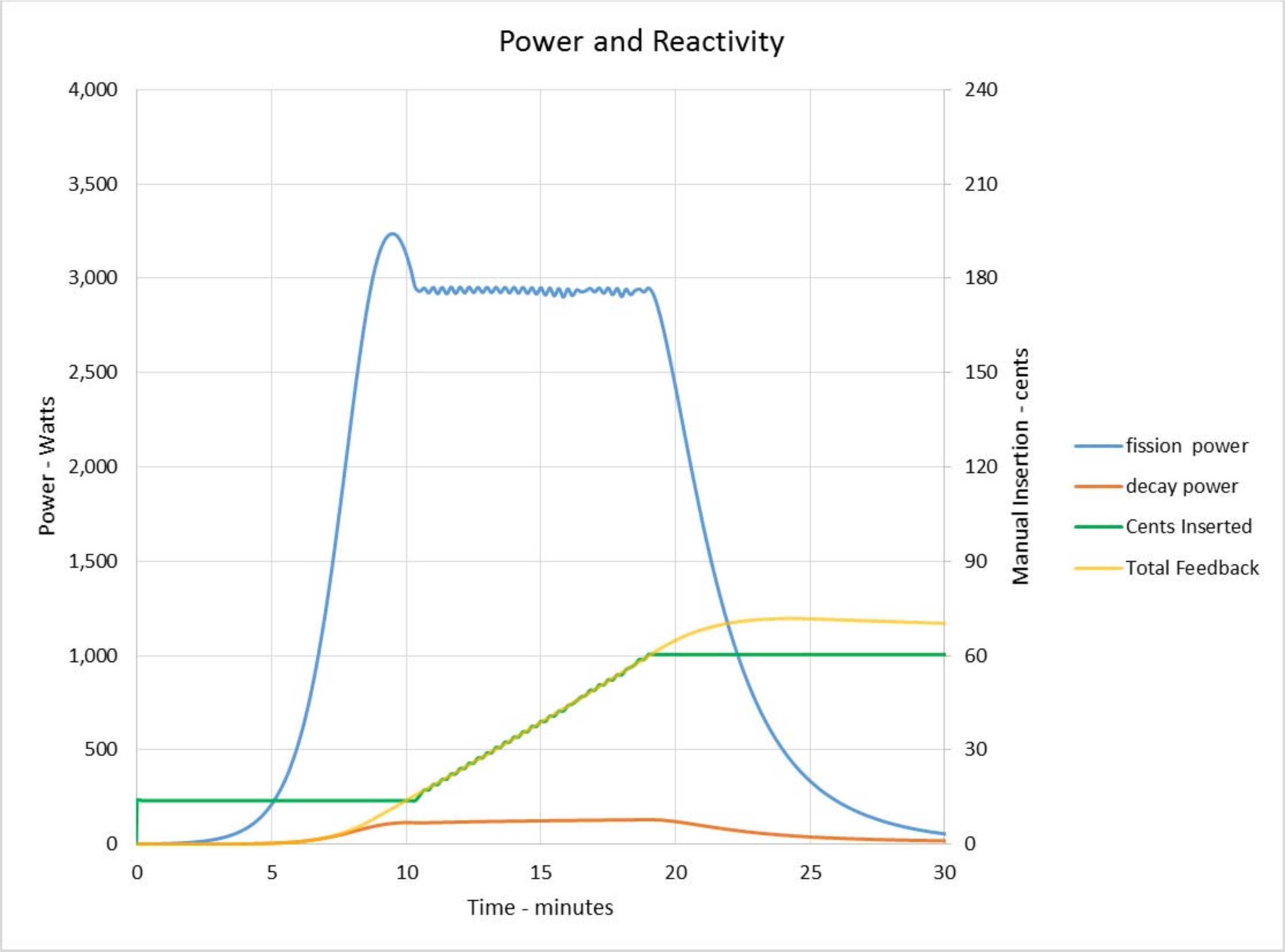




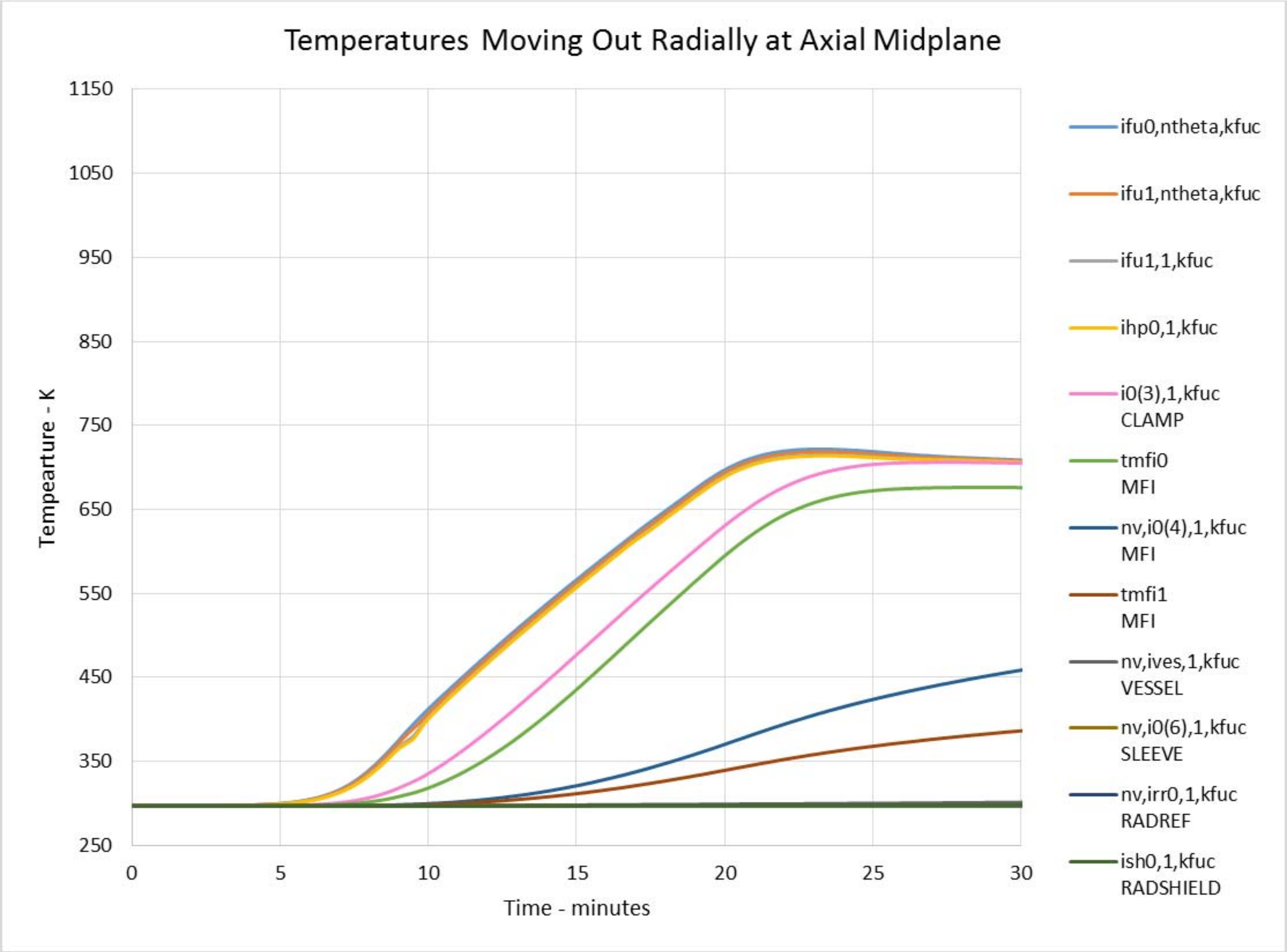




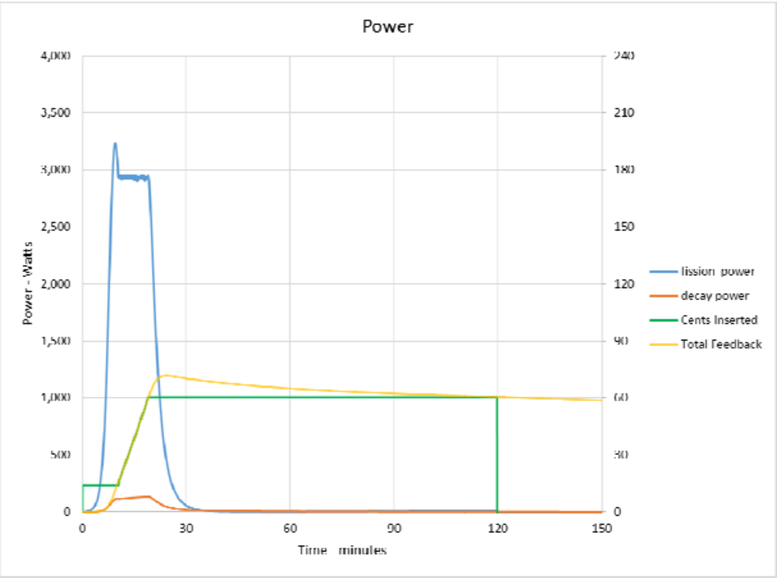
KRUSTY 60 cent run – 1st 30 min.

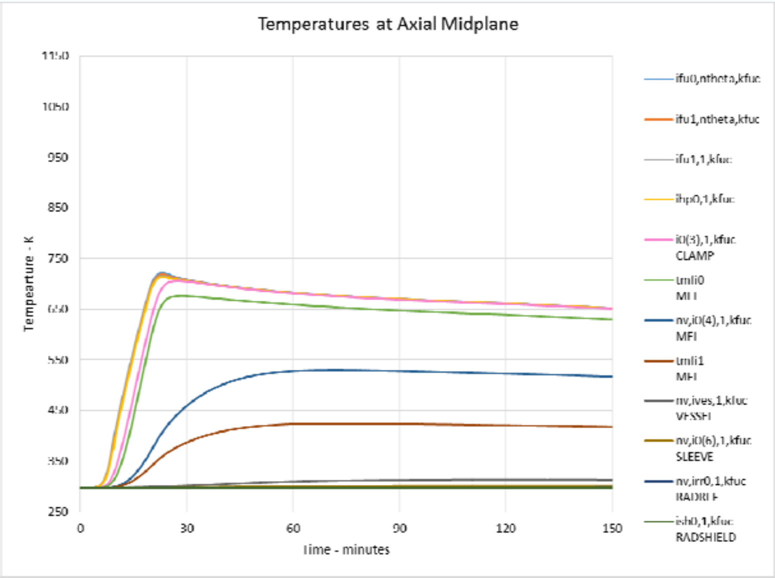


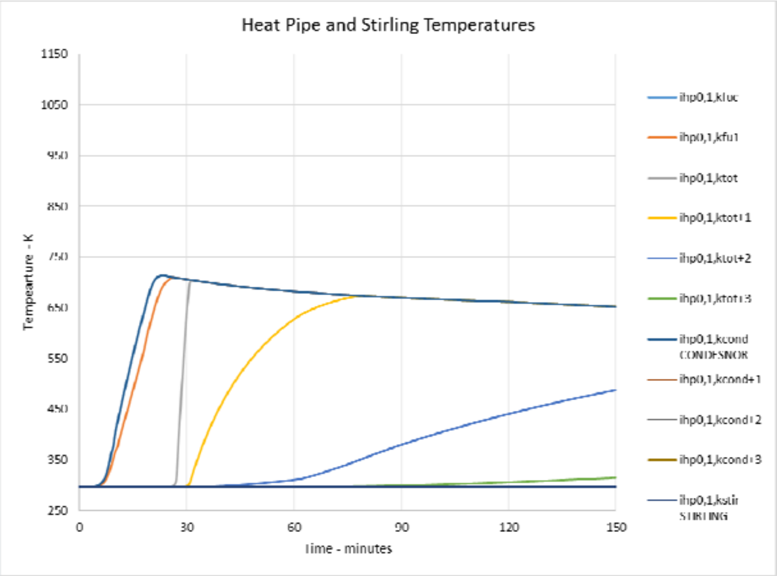
KRUSTY 60 cent run – 1st 30 min.

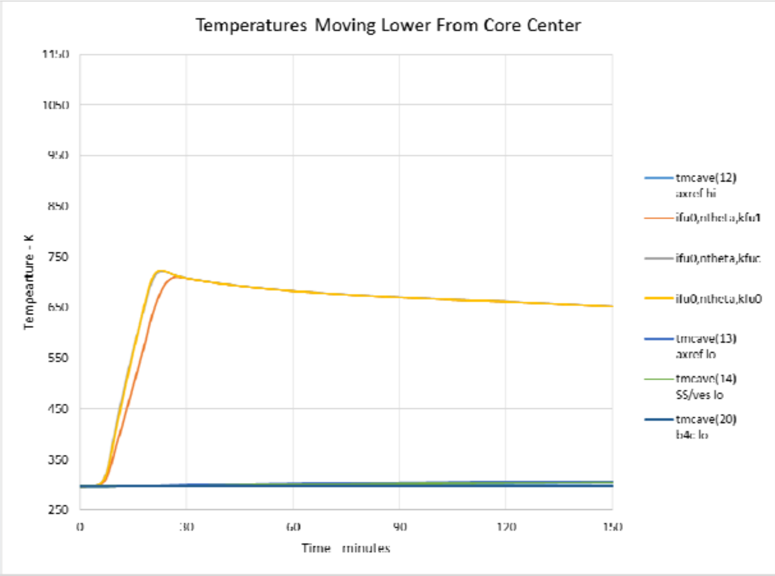


KRUSTY 60 cent run
2 hours them scram

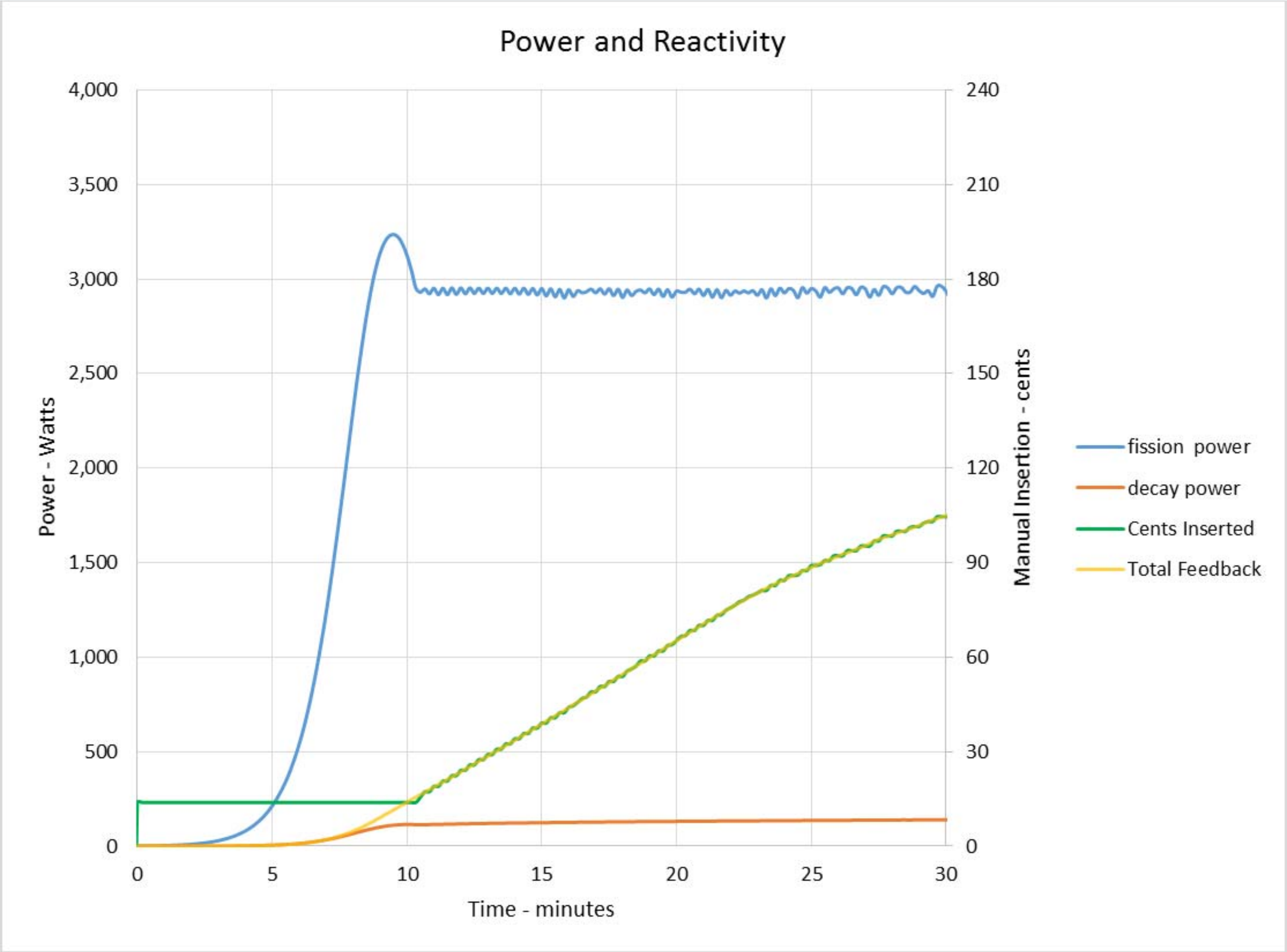




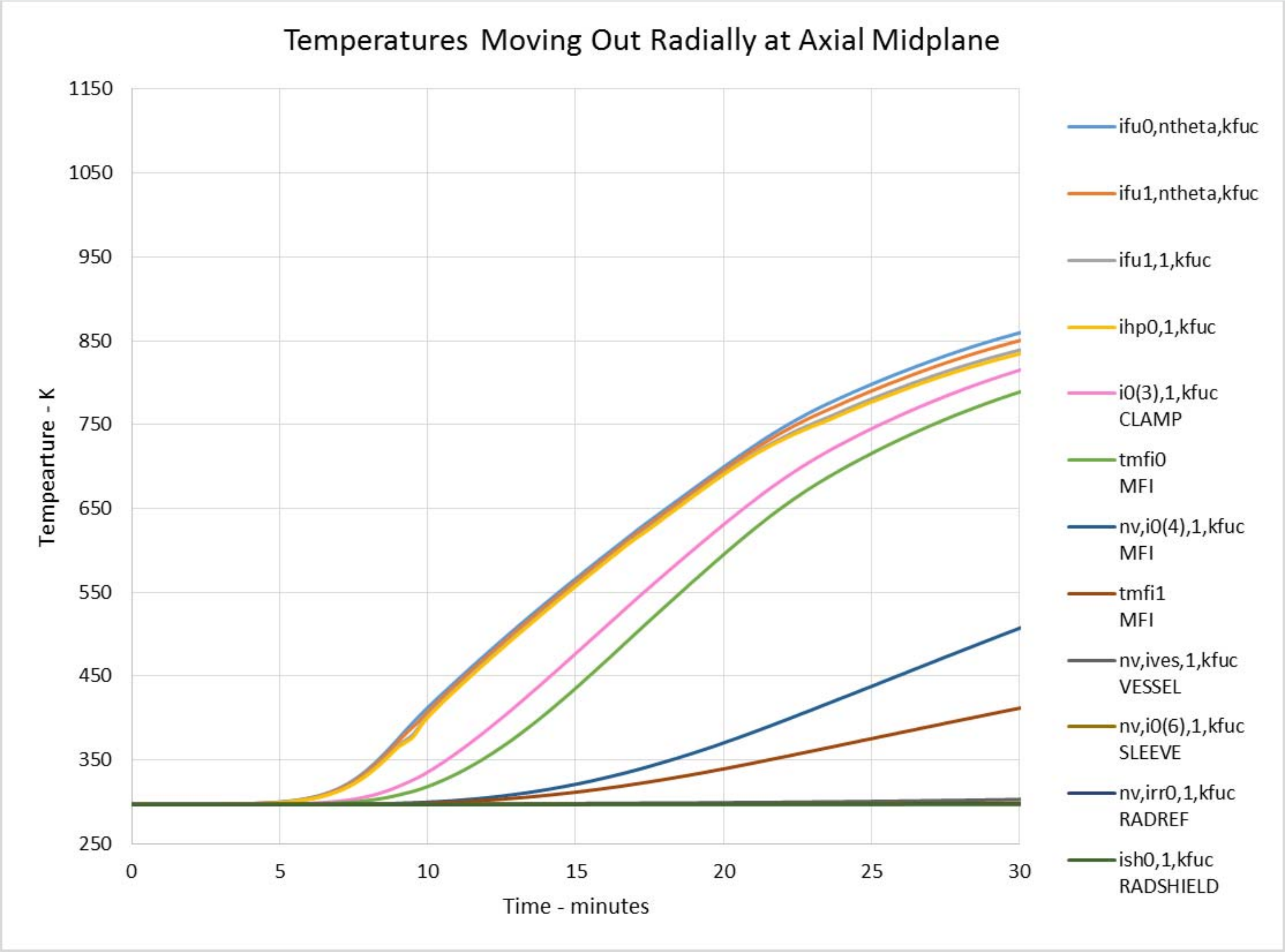




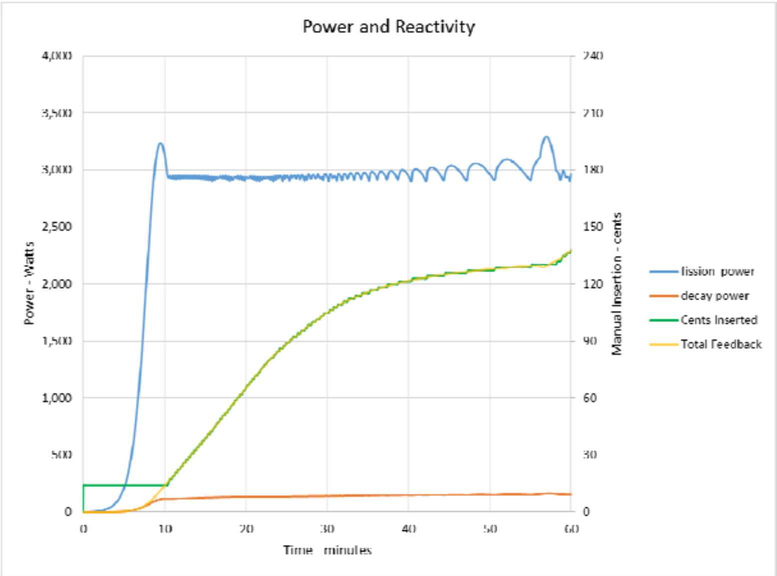
KRUSTY final run – 1st 30 min.

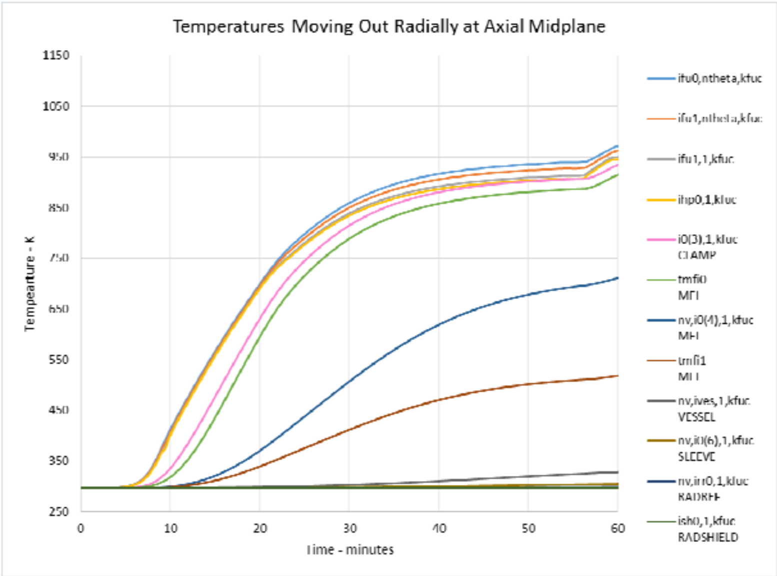


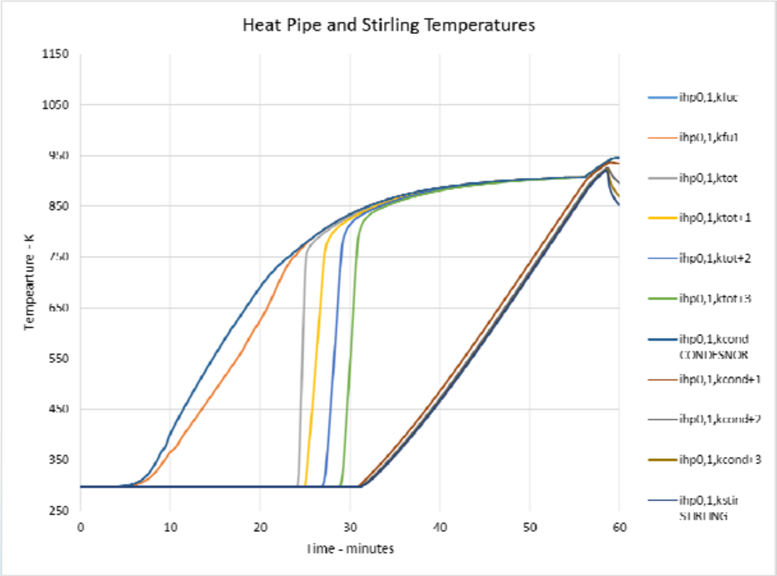
KRUSTY final run – 1st 30 min.

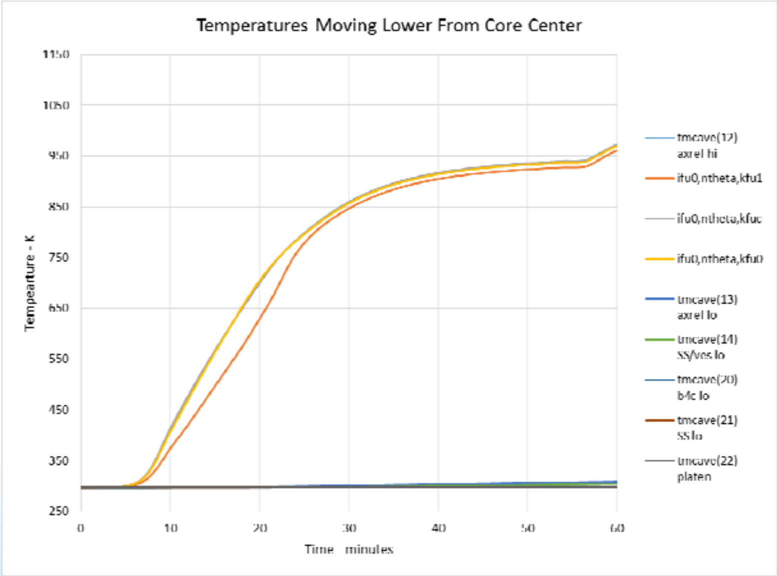


Nominal full power/temp run (1st hour)

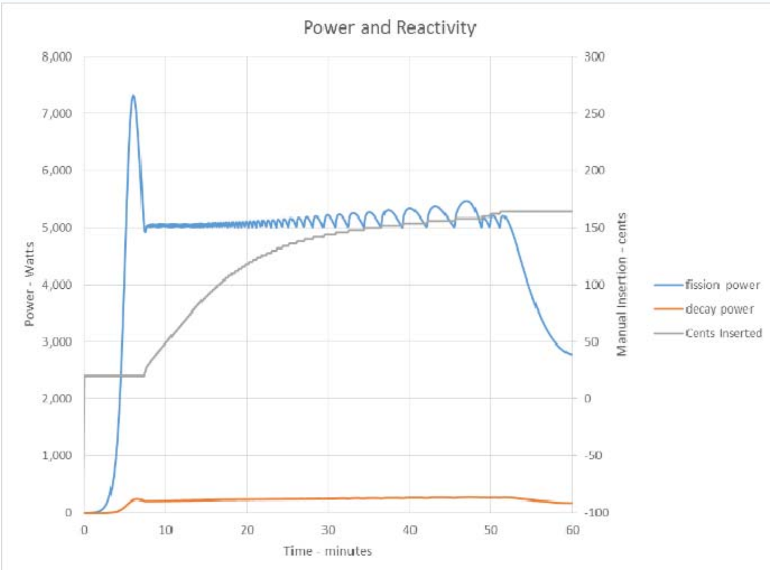


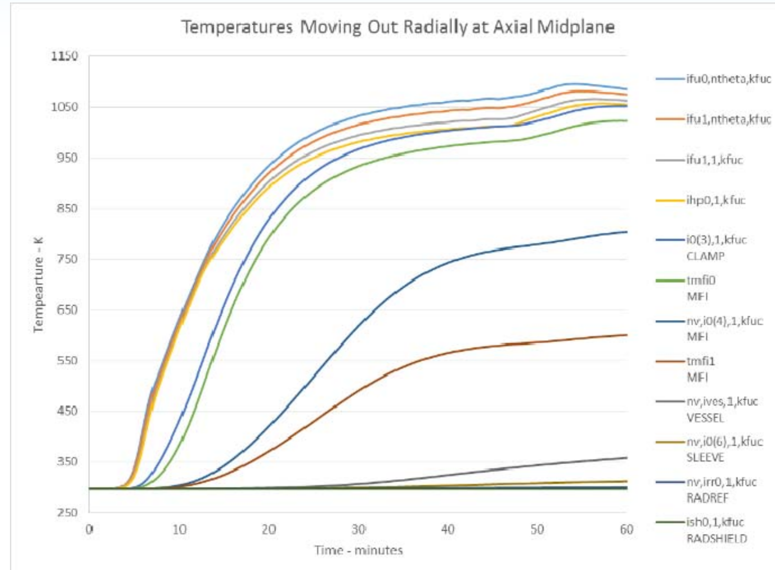


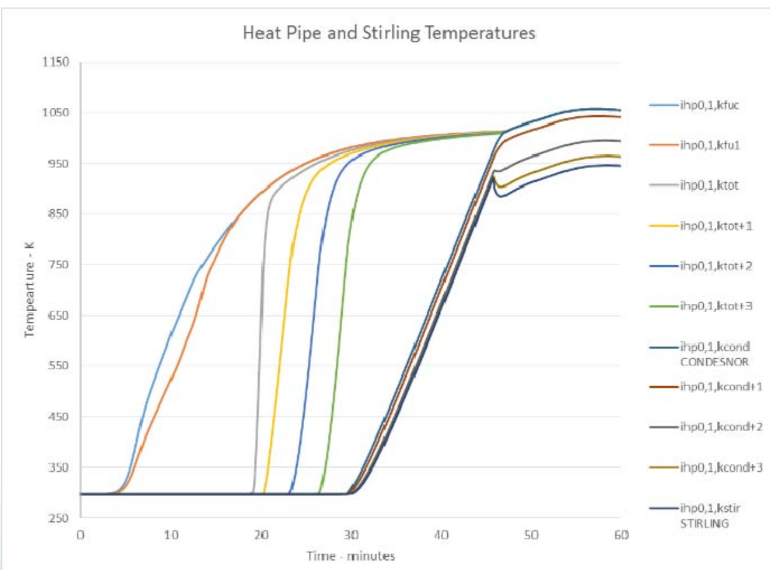


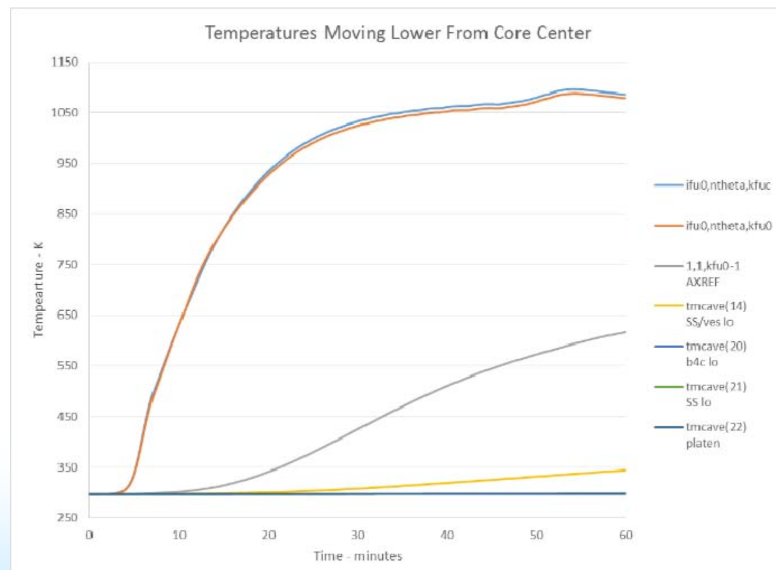


Older higher-power proposed test (1st hr)

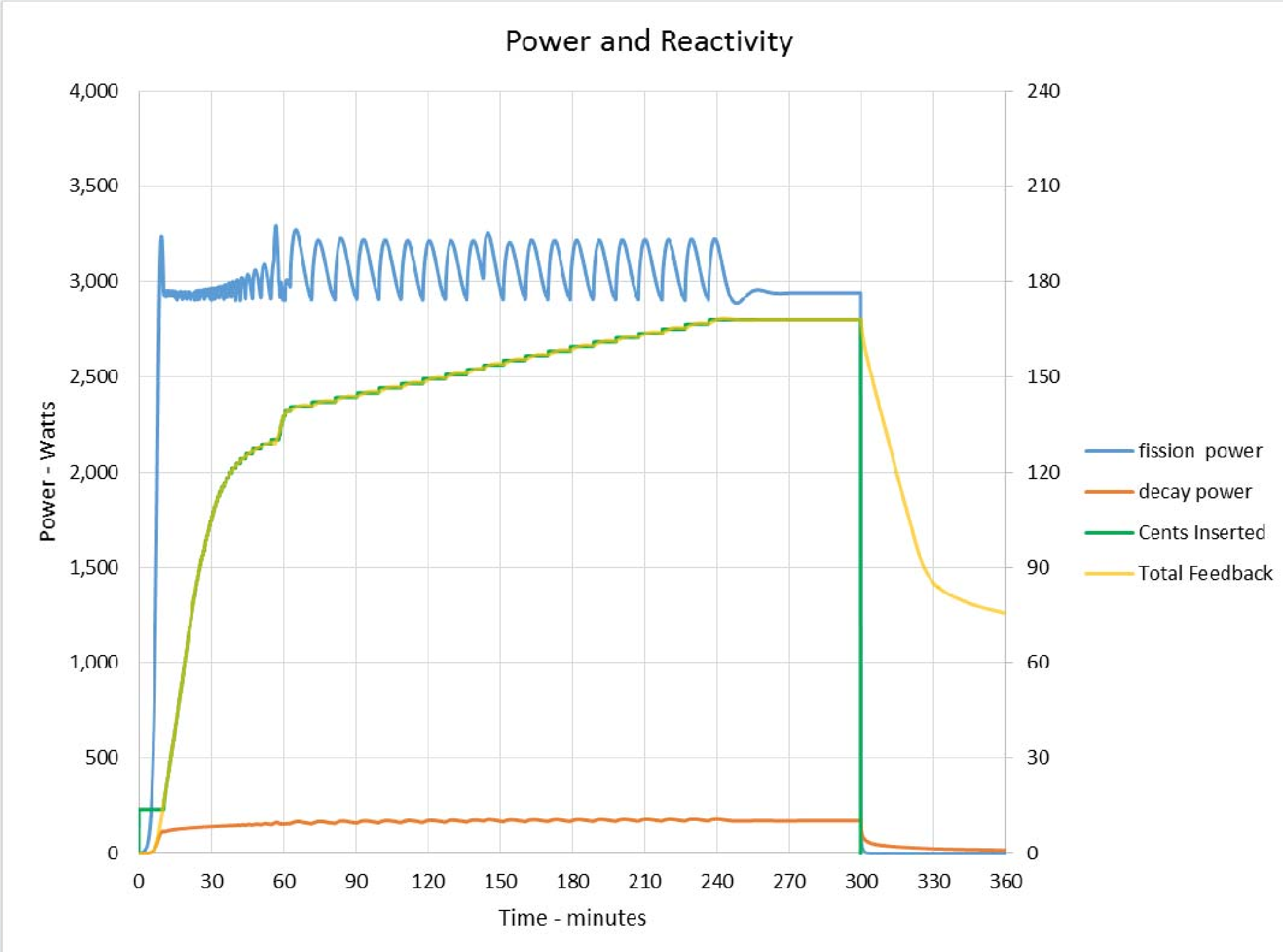




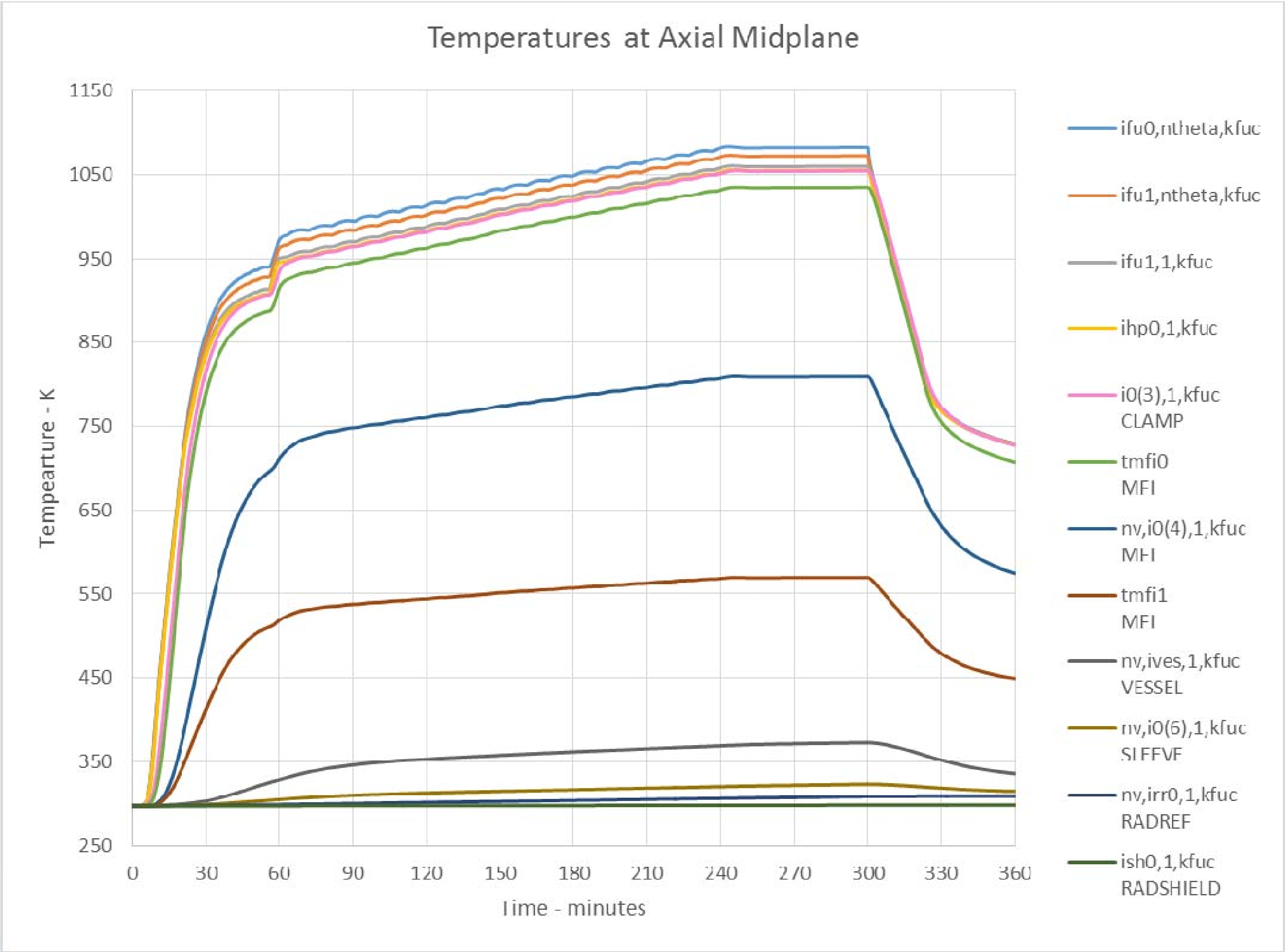




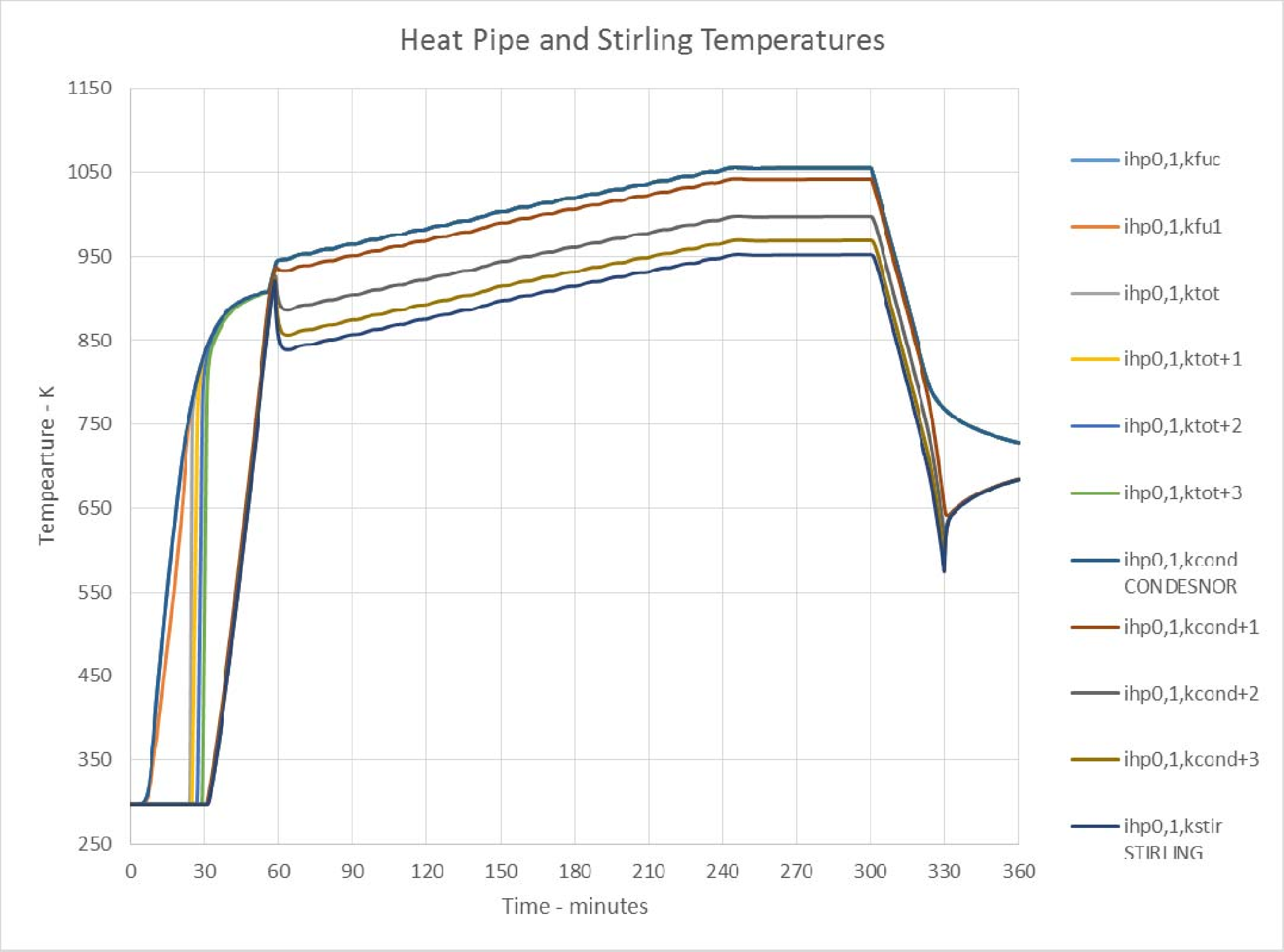
Full Run – although scram @ 5 hours



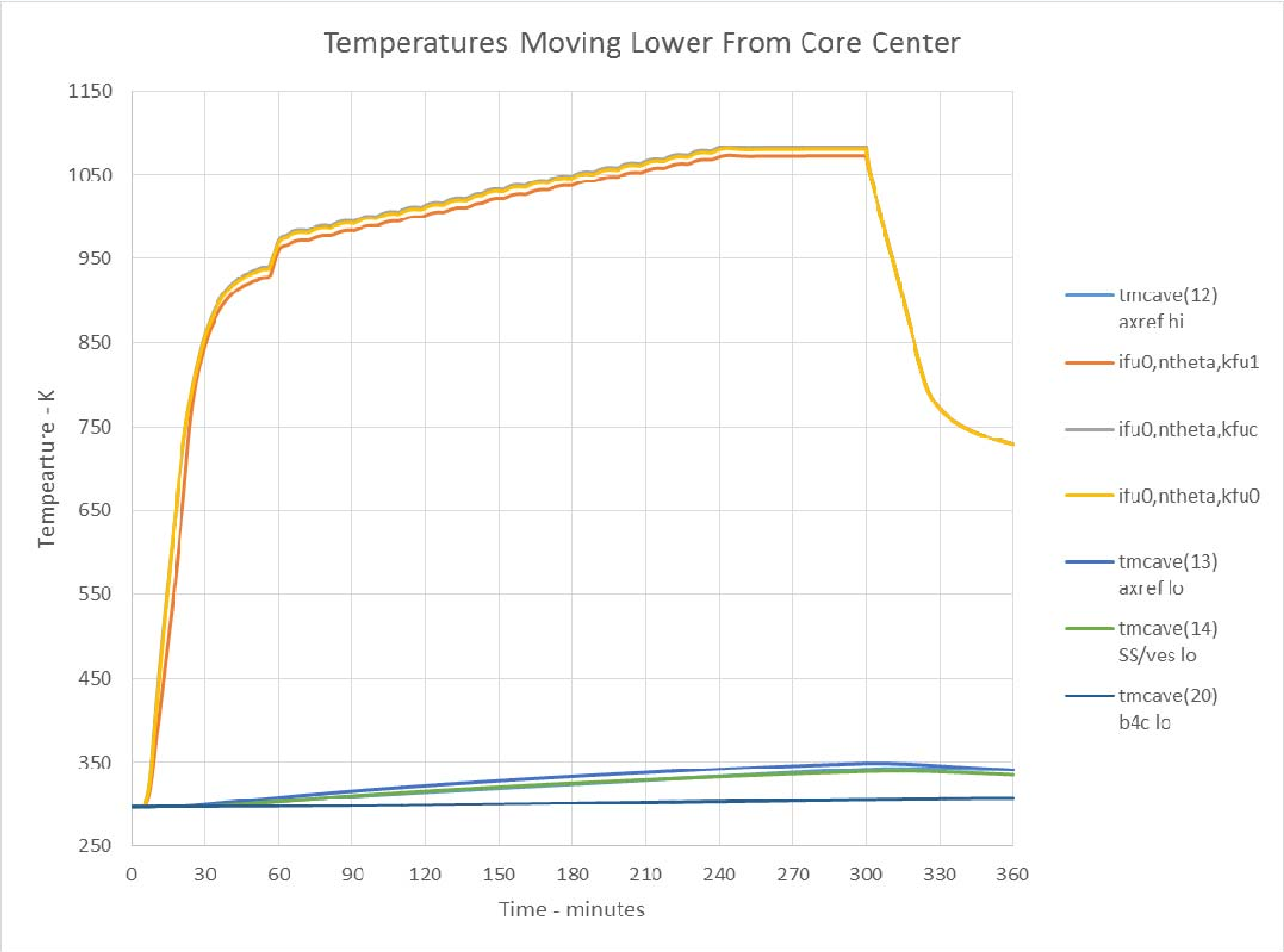
Full Run – although scram @ 5 hours



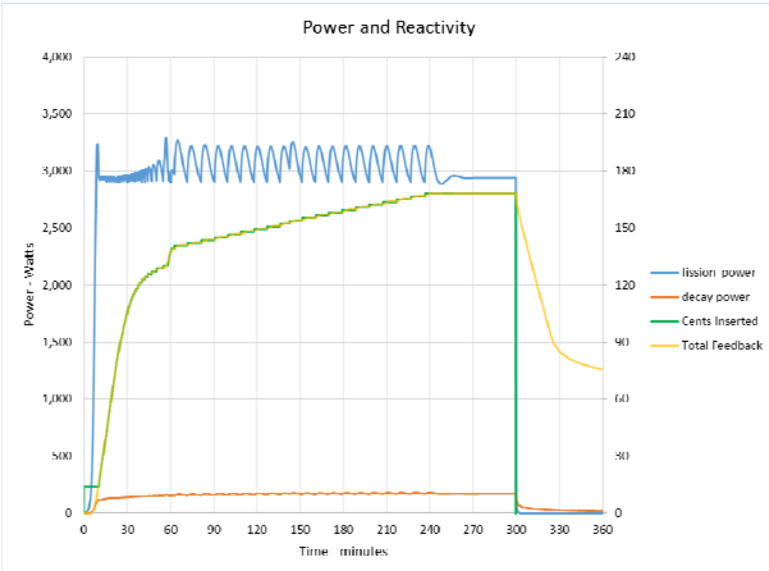
Full Run – although scram @ 5 hours

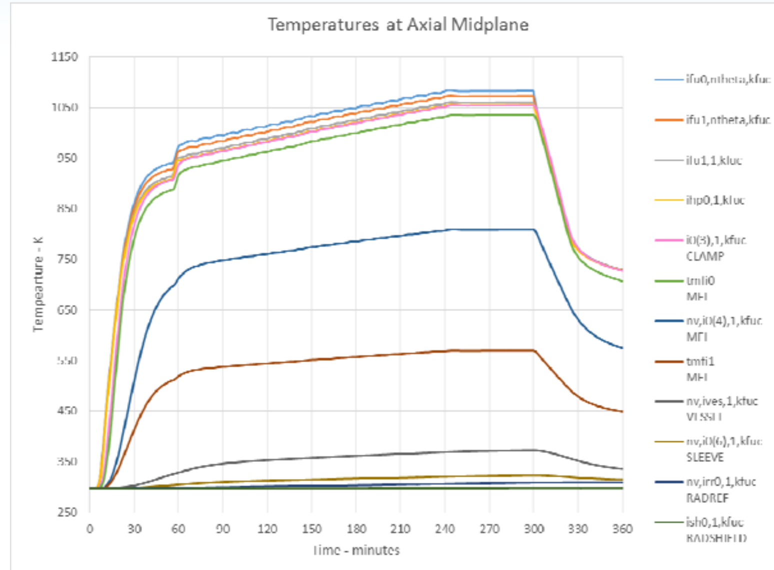


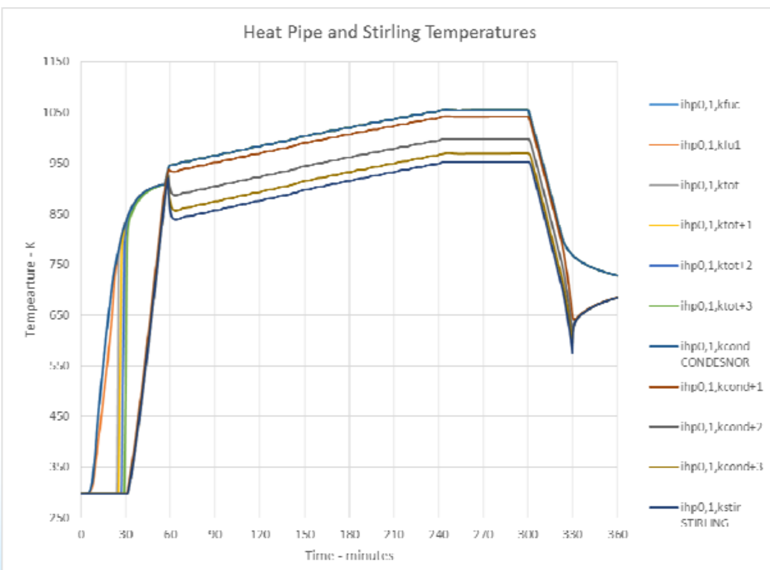
Full Run – although scram @ 5 hours

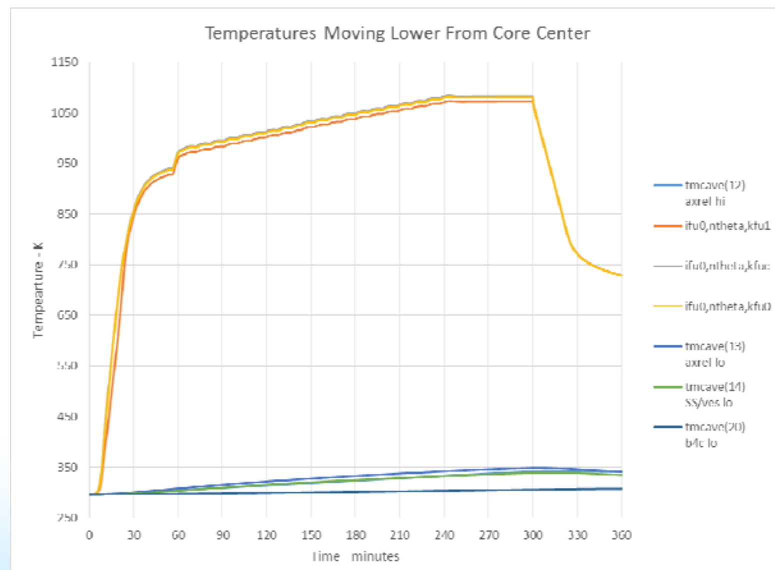


Full Run – although scram @ 5 hours

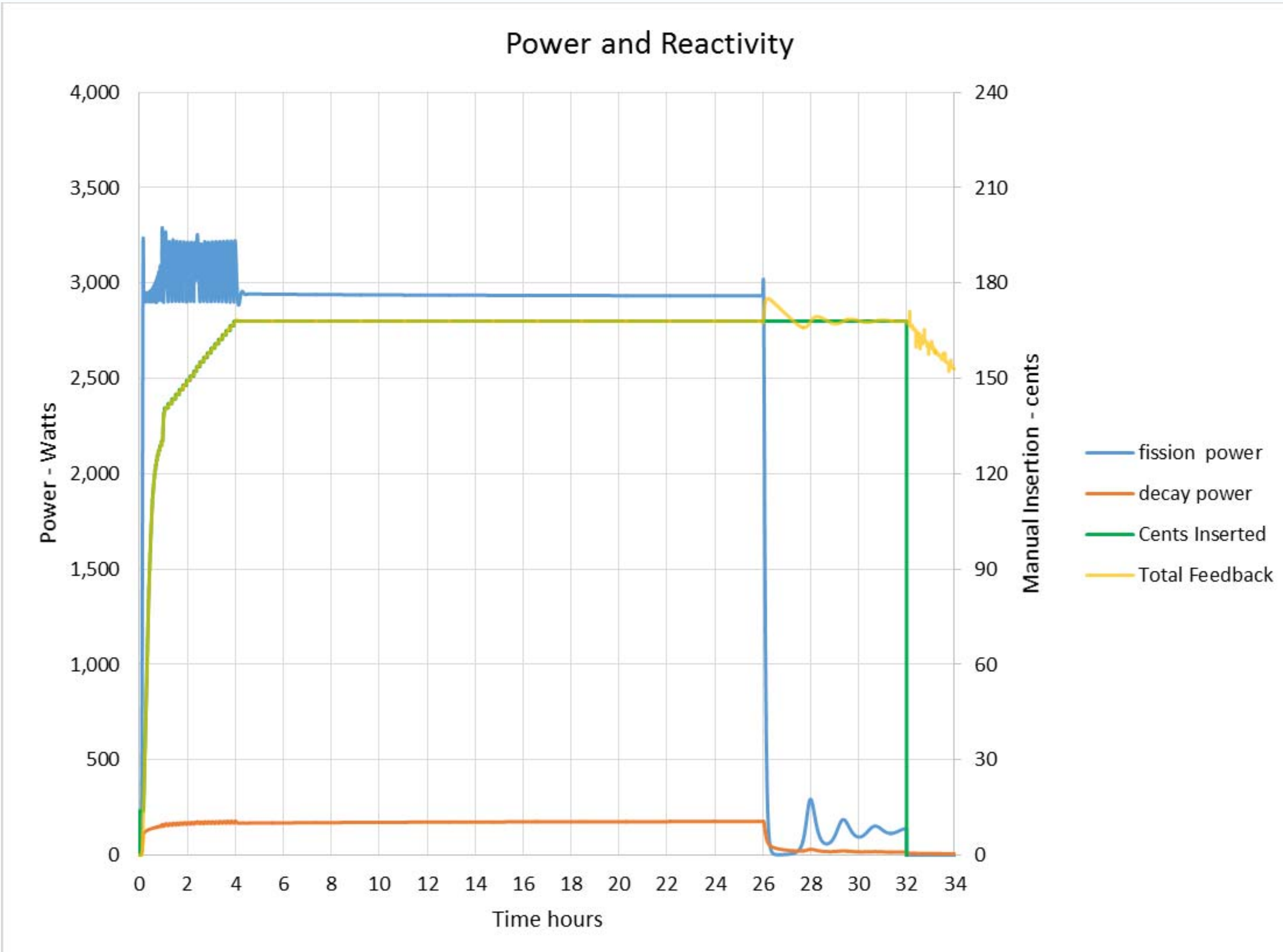






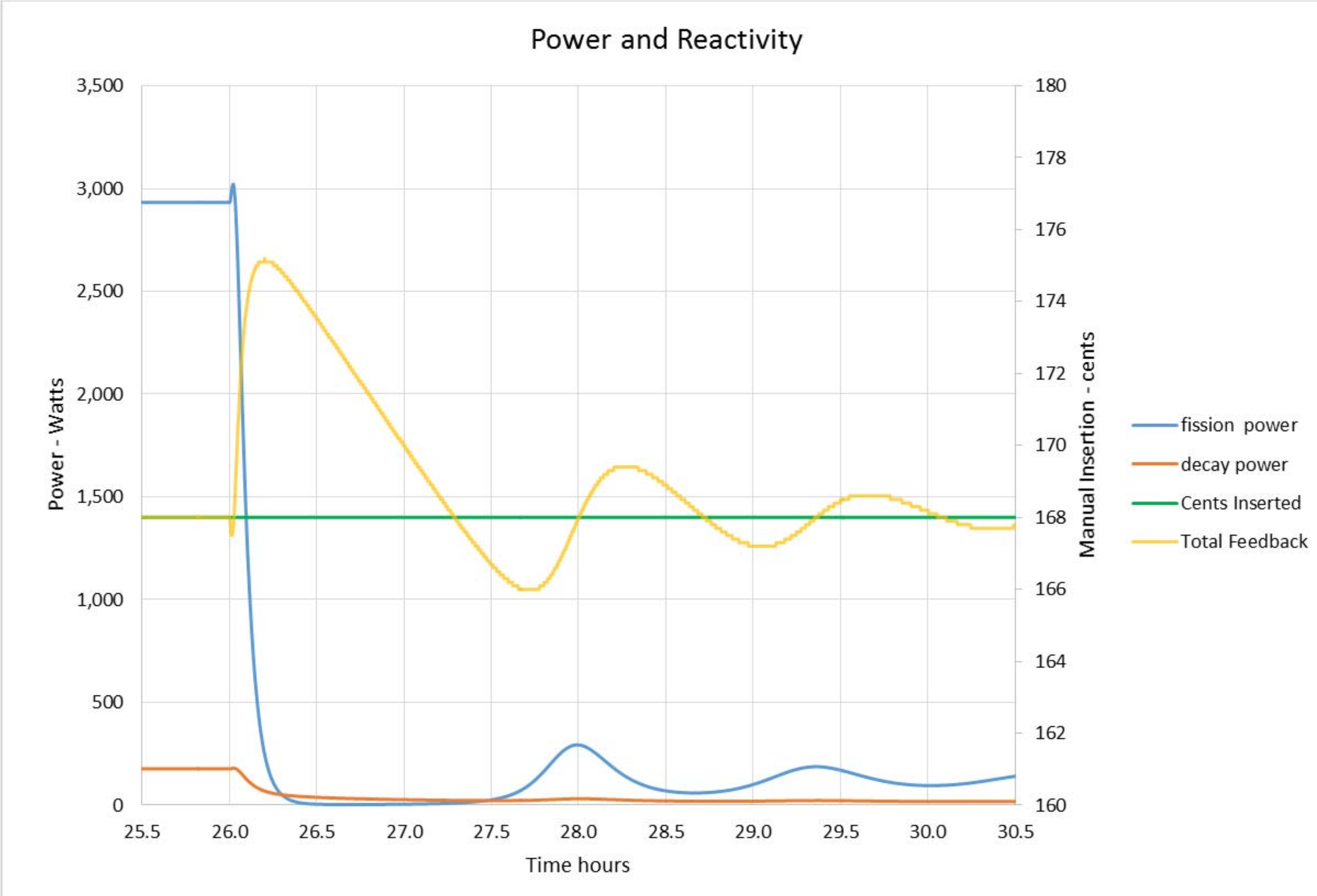


Full Run – Turn off Power Removal @ 26 hours, scram @30 hours



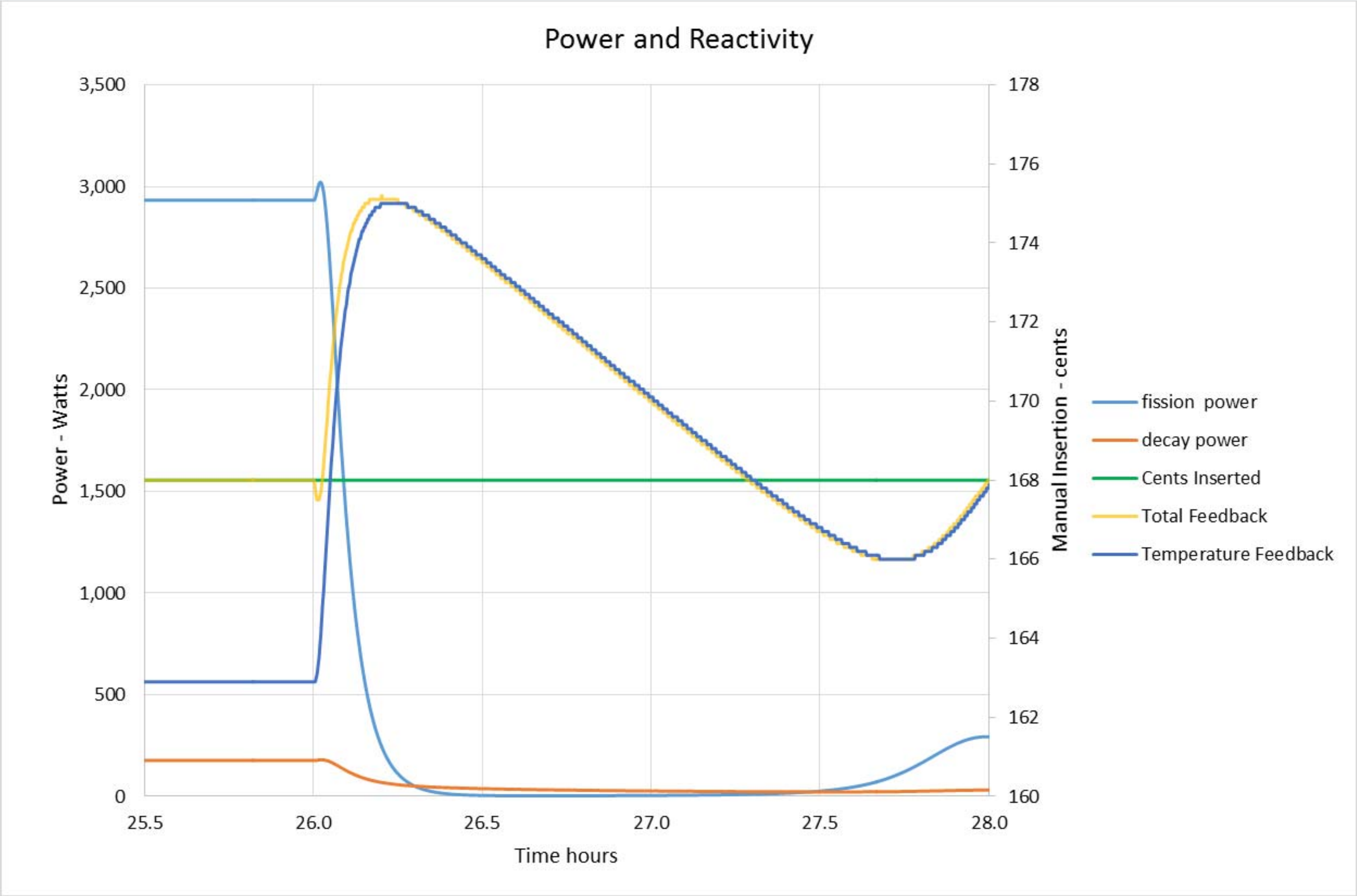
All of the reactivity insertion and heating takes place in the first 3 hours and then the system coasts for another 23 hours. At that point, the gas-flow through the Stirlings and Simulators is cut (and Stirling stroke is cut). Then the system settles to a new steady state power = power leakage from core. Then scram.

Full Run – Turn off Power Removal @ 26 hours, scram @30 hours



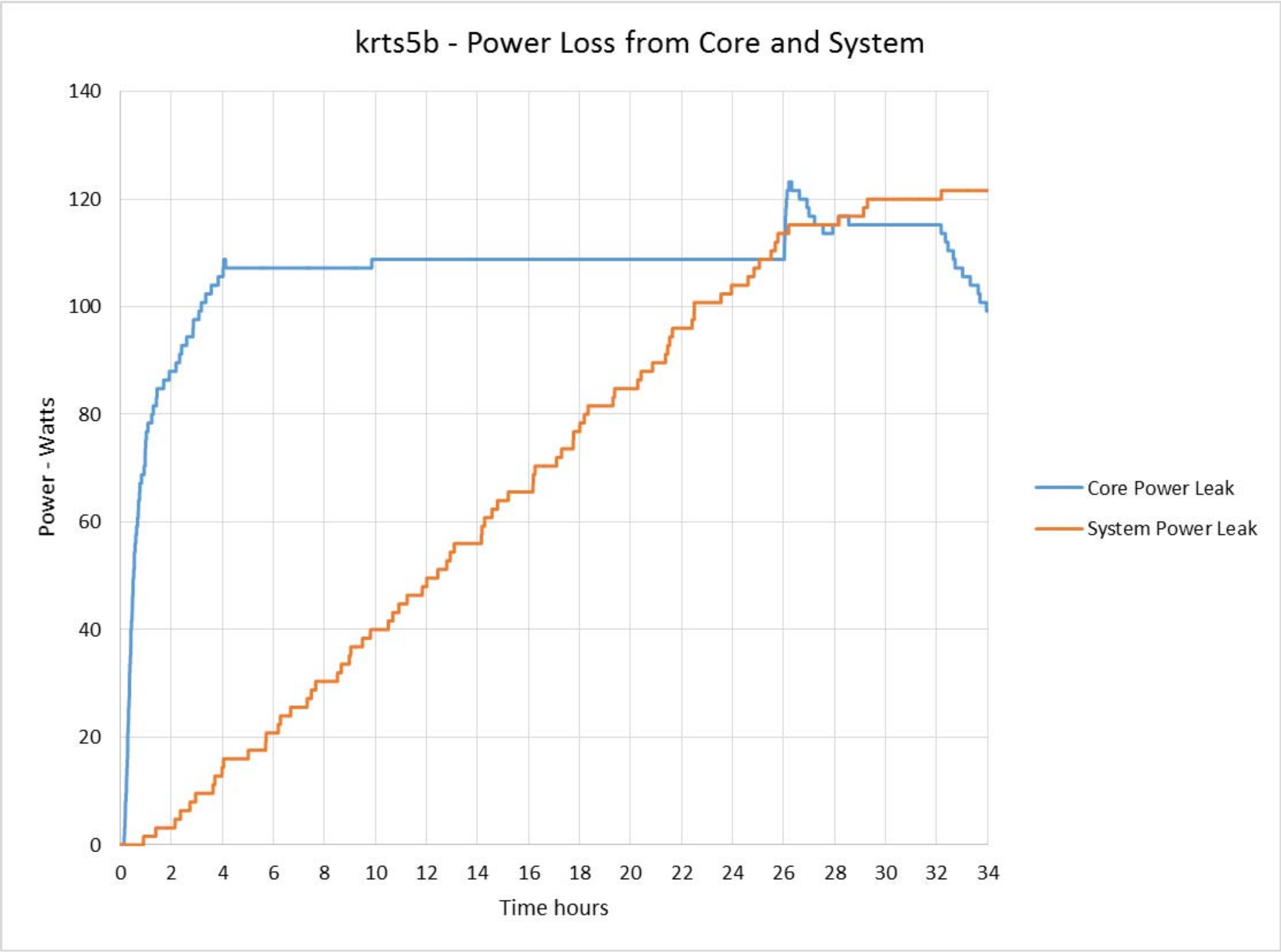
This is a closer look at reactivity and power after the power removal is cut. The yellow line shows the reactivity feedback, which in turn affects the fission power.

Full Run – Turn off Power Removal @ 26 hours, scram @30 hours



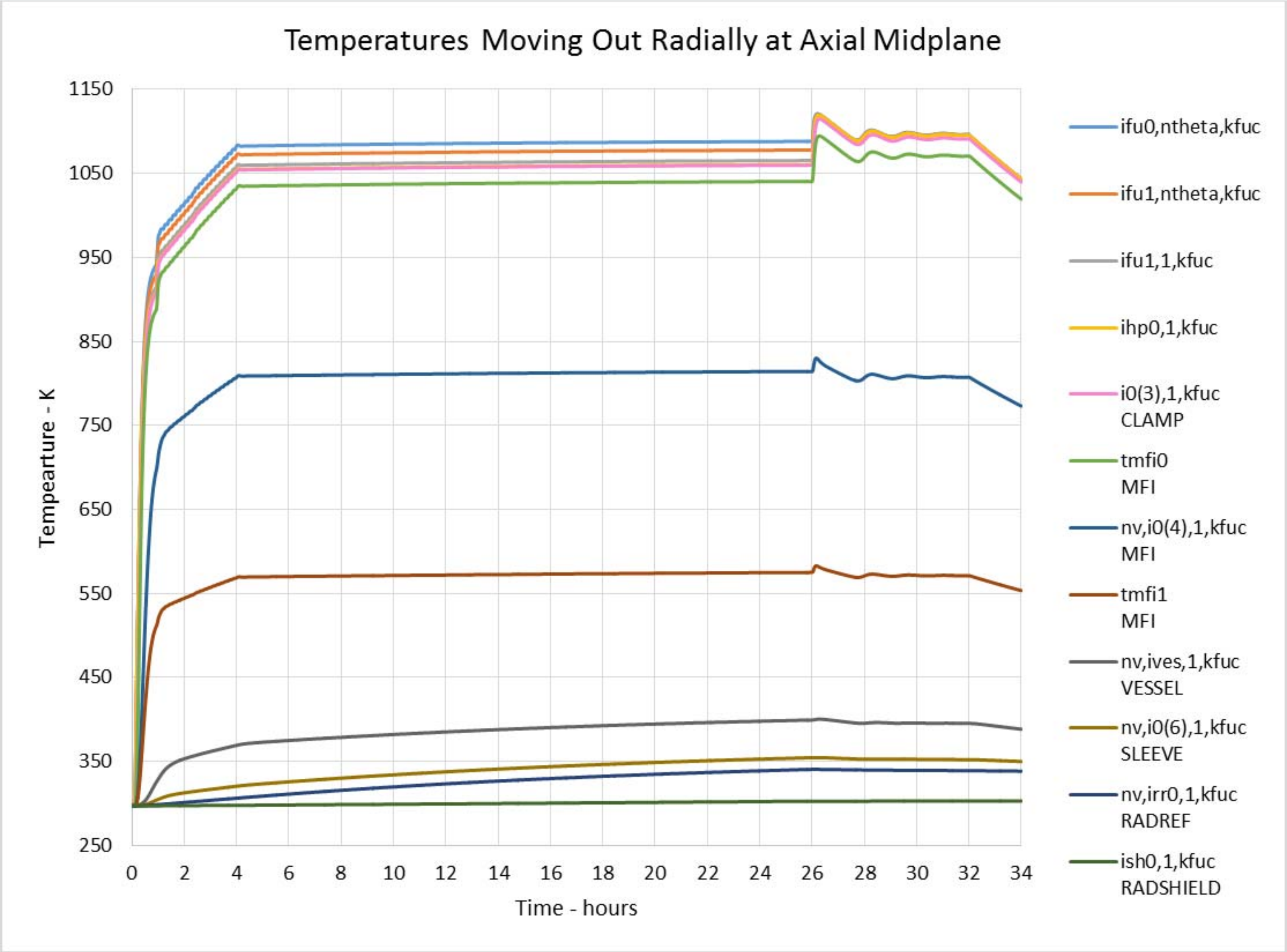
An even closer look shows an initial decrease in feedback, and subsequent increase in power in the first few minutes after power removal is cut. This is the effect of the Na in the heat pipe settling back down into the pool once the heat pipe is not longer transporting heat. The difference between the total feedback and the temperature feedback represents the pool feedback, which is 168 – 163 = 5 cents (at a power of 3 kWt).

Full Run – Turn off Power Removal @ 26 hours, scram @30 hours



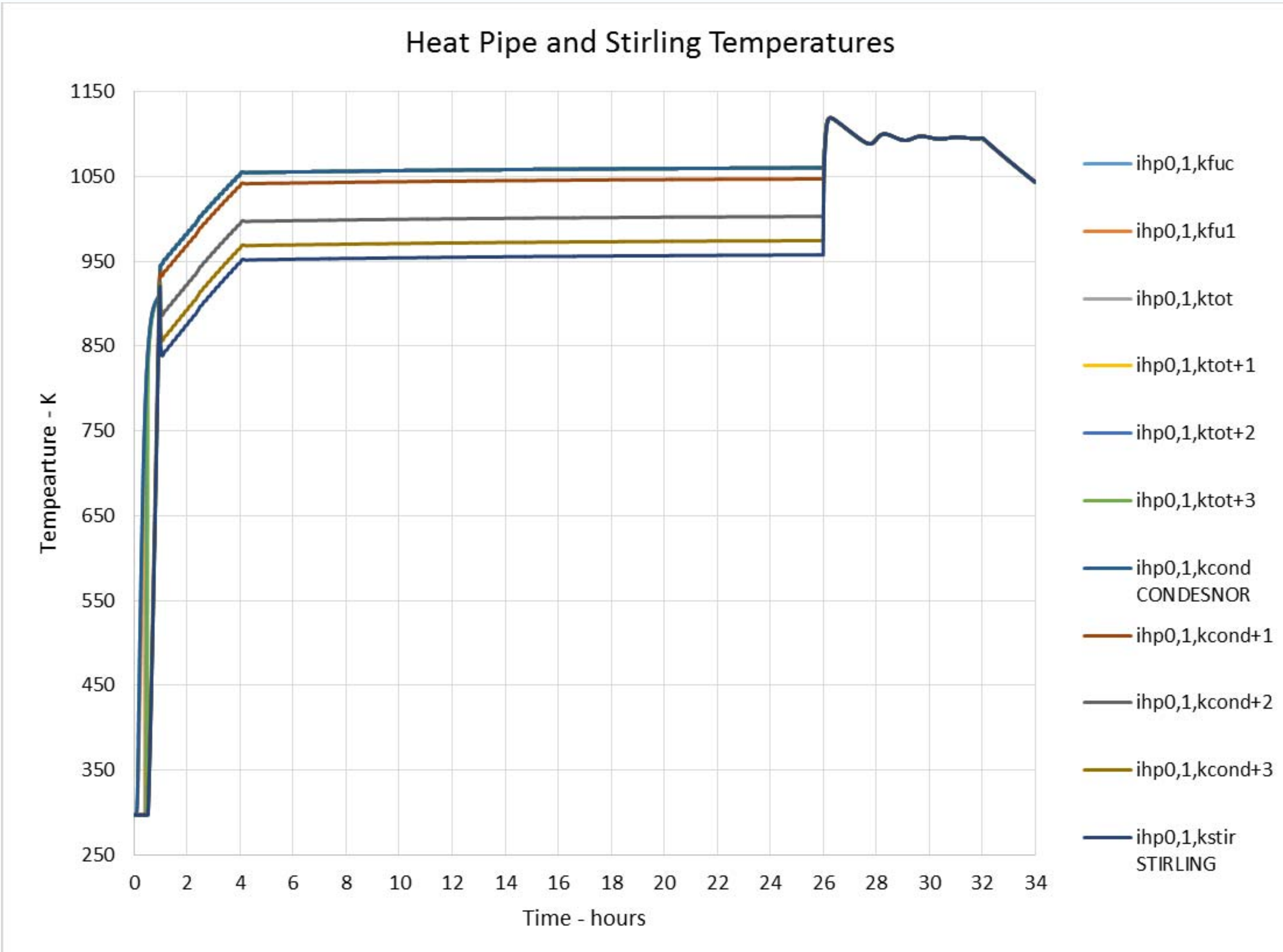
This chart shows the power "leakage" from core through the radial/axial mli (which reaches steady-state at ~110 W), and rejection from the system to the room. The latter is not yet to steady-state, which would be expected to top out at ~280 W (110 leak from core and 170 W of ex-core power deposition) – this would likely occur after 2 or 3 days. Pixelation is caused by poor formatting of output (only 2 significant digits).

Full Run – Turn of Power Removal @ 26 hours, scram @28 hours



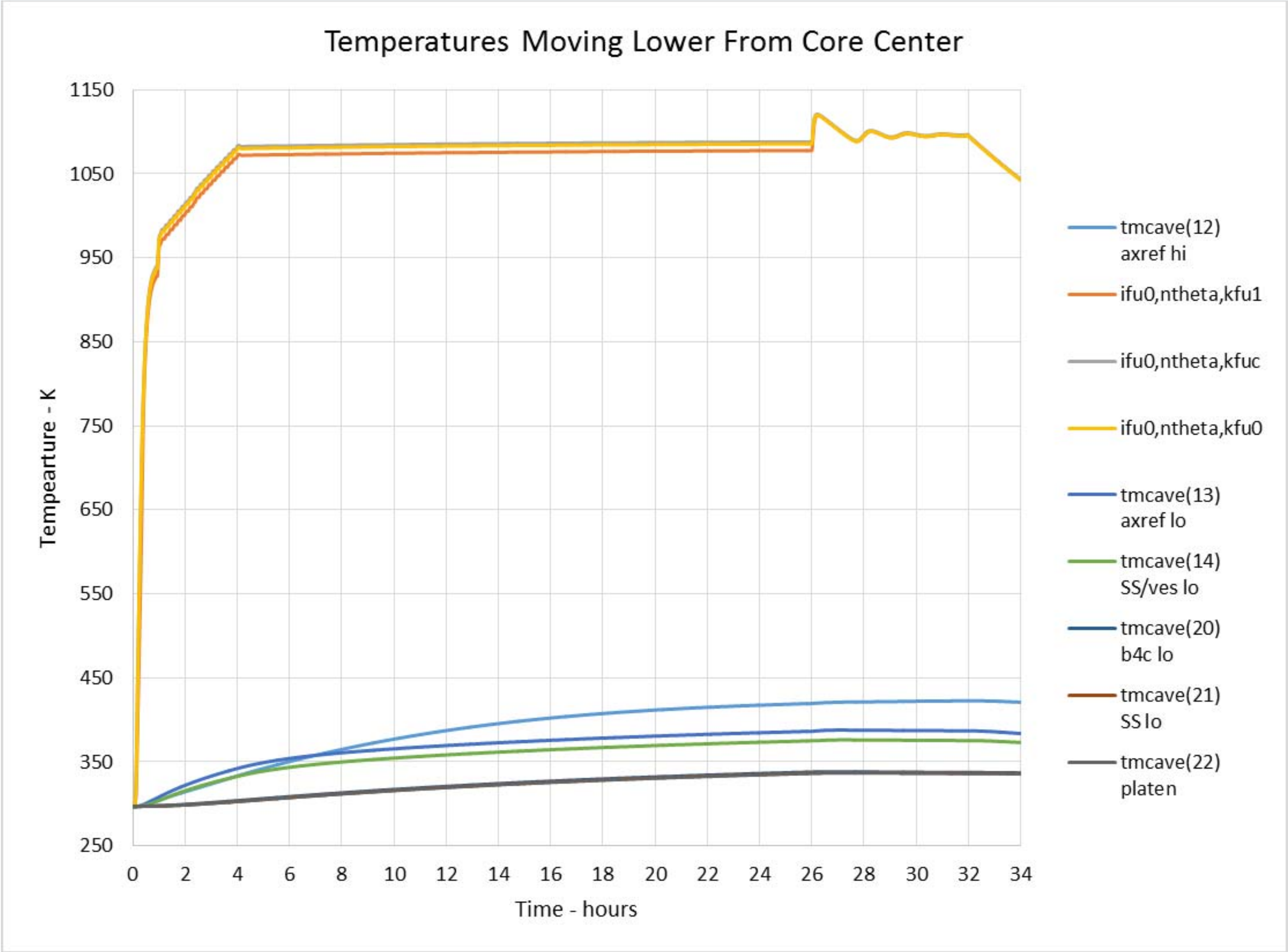
There will be various load following demonstrations added within the full run, but the piece de resistance is the ending, the elimination of all active power removal at T=26 hours in this case. Which is shown to be rather benign. This chart also shows the long term heating of various components. After a full day of operation, the radial shield has still only heated 5 degrees.

Full Run – Turn of Power Removal @ 26 hours, scram @28 hours



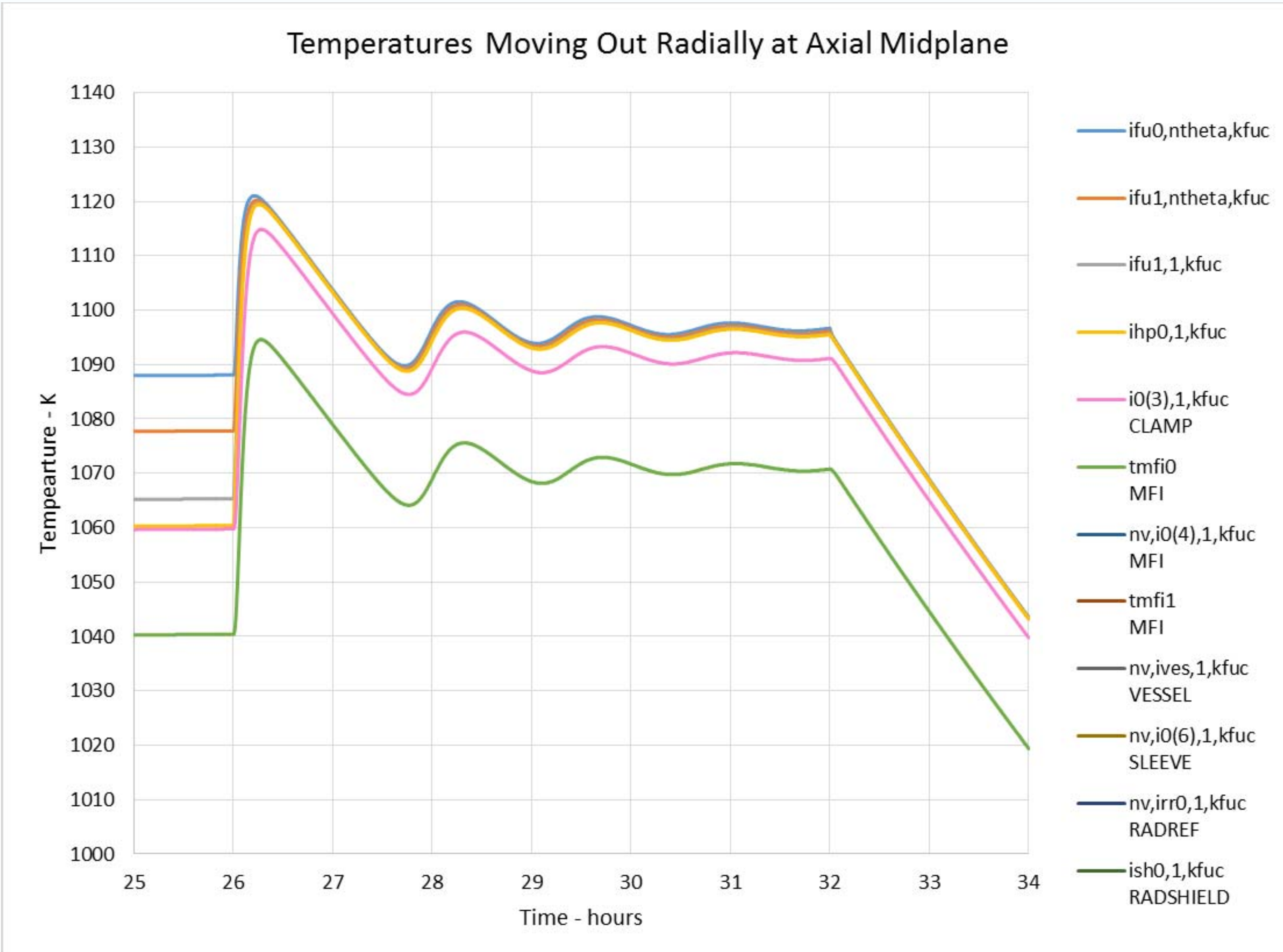
After power removal is cut, the temperature gradient from the heat pipe to the Stirling gas disappears, and all of the components are soaked to the same temperature (~1100 K).

Full Run – Turn of Power Removal @ 26 hours, scram @28 hours



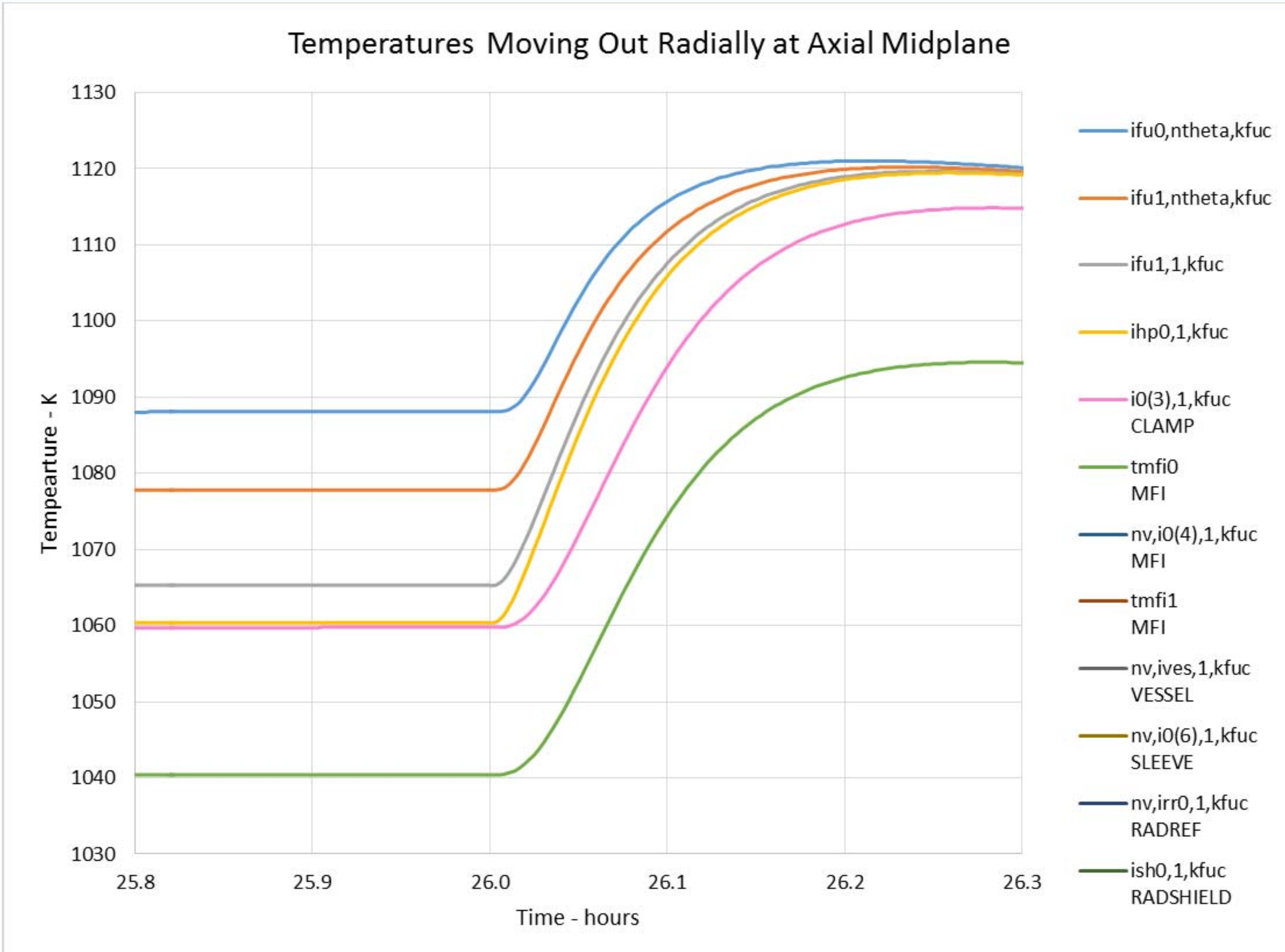
The components below the core heat up a bit more than the radial components because there are fewer radiation gaps, plus the mli is assumed to be compacted such that it's conductance is increased by a factor of 4 over the radial mli. The model shows the lower shielding and platen heating up 30 degrees.

Full Run – Turn of Power Removal @ 26 hours, scram @28 hours



Upon loss of heat sink, the peak fuel temperature rises ~30 K and then the entire core settles an equilibrium temperature just below 1100 K. At scram, the core power of ~140 W cuts off, and temperatures start to drop.

Full Run – Turn of Power Removal @ 26 hours, scram @28 hours



A closer look best shows the peak fuel temperature rise is of 30 K, and average rise of ~50 K. Note the HP and clamp are both ~1060 at steady-state, but the HP follows the fuel to an isothermal core temp, while clamp remains lower.

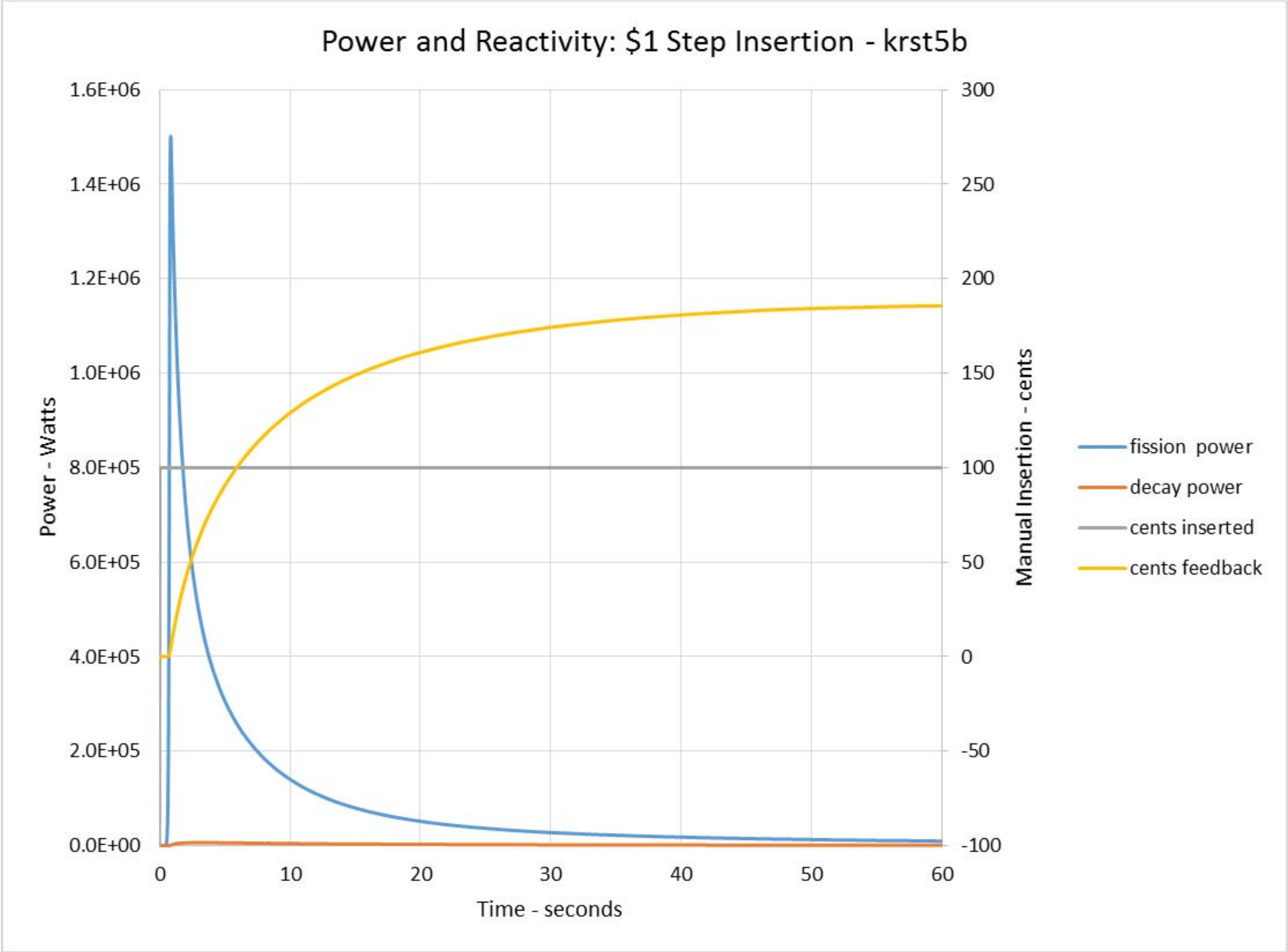
Instantaneous (Step) Prompt Insertions

- A step-insertion if defined at the point (reactivity) when a chain-reaction is sustained
  - E.g. a \$1 step-insertion means that a sustained chain reaction (or sensible heating/feedback) does not begin until the system reaches \$1 of reactivity.
    - It is the same as if the reactivity was introduced instantaneously (e.g. platen was inserted infinitely fast).
- In a real, physical system, reactivity cannot be inserted in a perfect step (infinitely fast); i.e. it takes time for a system to move from subcritical to prompt supercritical.
  - However, a step insertion can occur if a chain fails to be establish in the time it takes to insert the reactivity.
- Prior to a sustained chain reaction, or initiation, neutron kinetics does not apply
  - When a system is supercritical (reactivity>0), neutron kinetics models will predict that the number of neutrons in each generation will increase.
    - E.g a keff of 1.01 indicates that 1 new neutron will be produced for every 100 in existence over the course of the neutron generation time.
  - For kinetics equations to “work”, the neutron population must be large (statistically significant) enough to average out the fact that each specific neutron must discretely die or produce 2 or 3 neutrons via fission.
    - If there is a low enough population, it can be much more likely that a chain fizzles out than becoming sustained; even if the neutron population in the 1000s (depending on magnitude of the “step”)
- The probability of a step insertion depends on…
  - How long it takes to insert the reactivity
    - First order, probability of step decreases linearly with time
  - The rate at which “stray” neutrons interact with the fuel (i.e. the neutron source)
    - First order, probability of step decreases linearly with source strength
  - The level of supercriticality
    - Probability of step decreases exponentially with higher reactivity – this is what makes large prompt step insertions so unlikely.

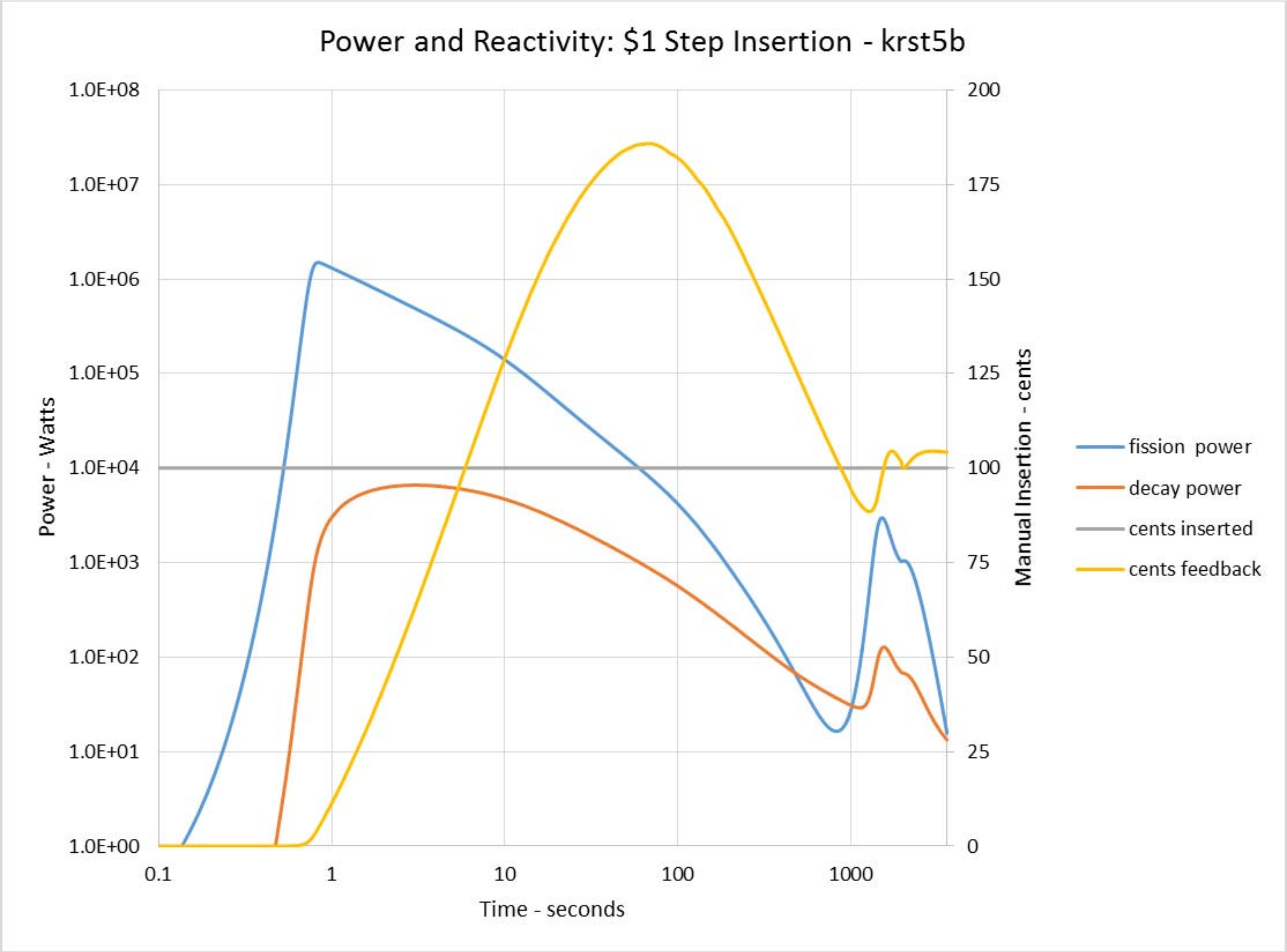
Instantaneous (Step) Prompt Insertions

- Step insertions of $1 and $1.4 above delayed-critical were evaluated with FRINK.
- FRINK does not contain physics above the Umo melting point, however the transient continues.
  - Although sometimes crashes does to bogus property polynomial values.
- Anything modeled above 1400 K is dicey.
  - Fuel melting point is ~1405 K, although Mo increases it a little.
  - Heat of fusion of U is 50 kJ/kg,
    - Given Cp of 220 J/kg-K at melting temp, then hfg is worth about 225 degrees of heat up.
    - Thus something at 1630 K on plot is likely melted, 1500 partly melted.
    - Hot spots will be internal, thus likely contained, until edge fuel melts 1400 K.
    - Mo has very high hfg, but would not reach melting point regardless.
- IMPORTANT: a step insertion of any kind is essentially impossible.
  - The operators' task is to keep the system near critical, and only slightly above critical (<15 cents) when starting up, which they easily monitor by watching the rate of power change.
  - If there is operator/system error that inserts to much reactivity, there is a platen speed limit programmed into comet, and at the programmed speeds of <.01"/s, which makes the probability of prompt step insertion astronomically low.
  - A neutron source will be present, with an effectiveness that will be demonstrated in the prior testing. This will make the probability of a prompt insertion (especially >>$1) very low even if the platen could move faster than is physically possible.
- These step calculations are useful mostly to test FRINK point kinetics (i.e. does reactor period match, pulse shape, number of fissions, etc. match theory) and to give some insight into system transient response.

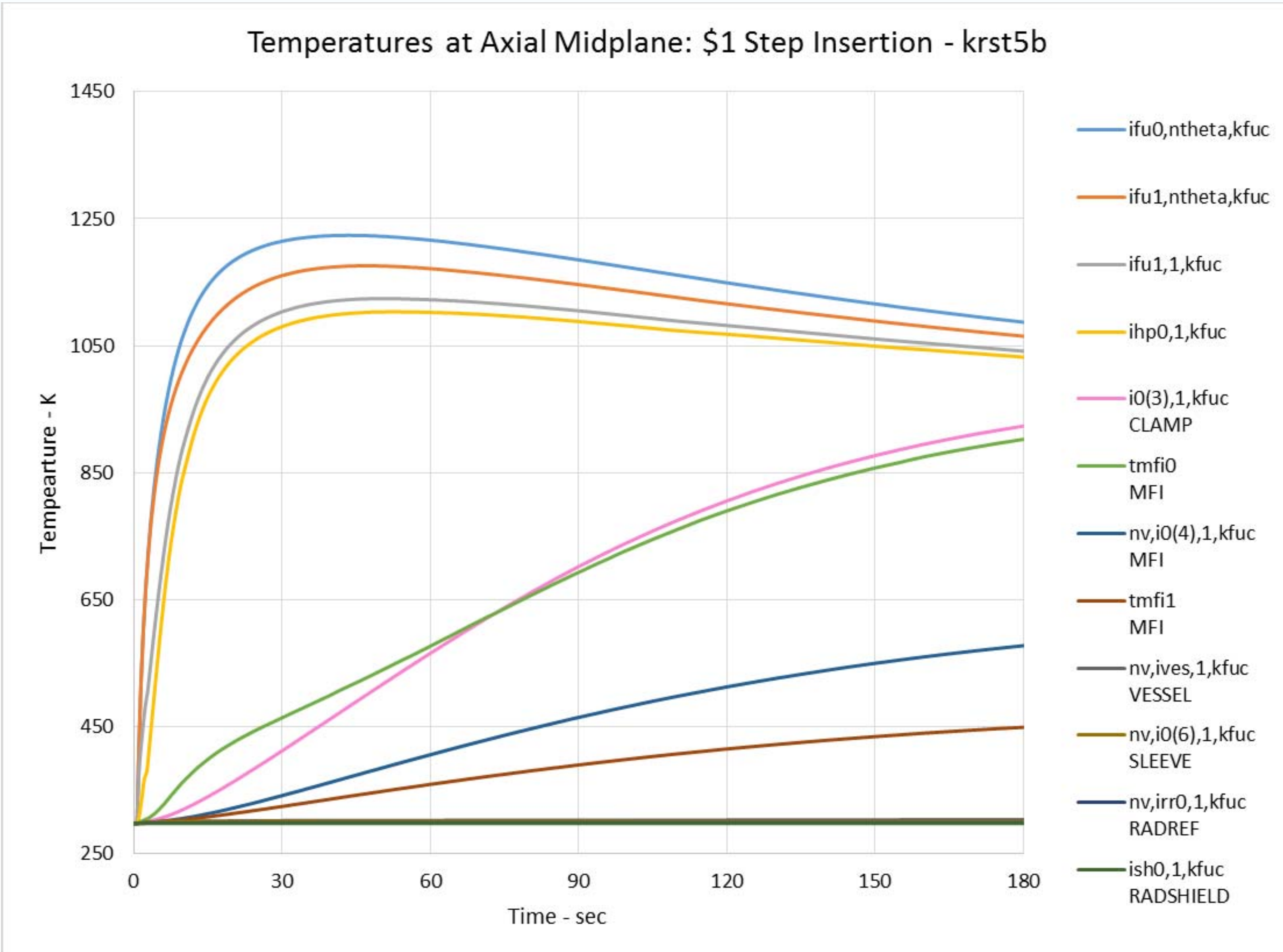
$1 Instantaneous



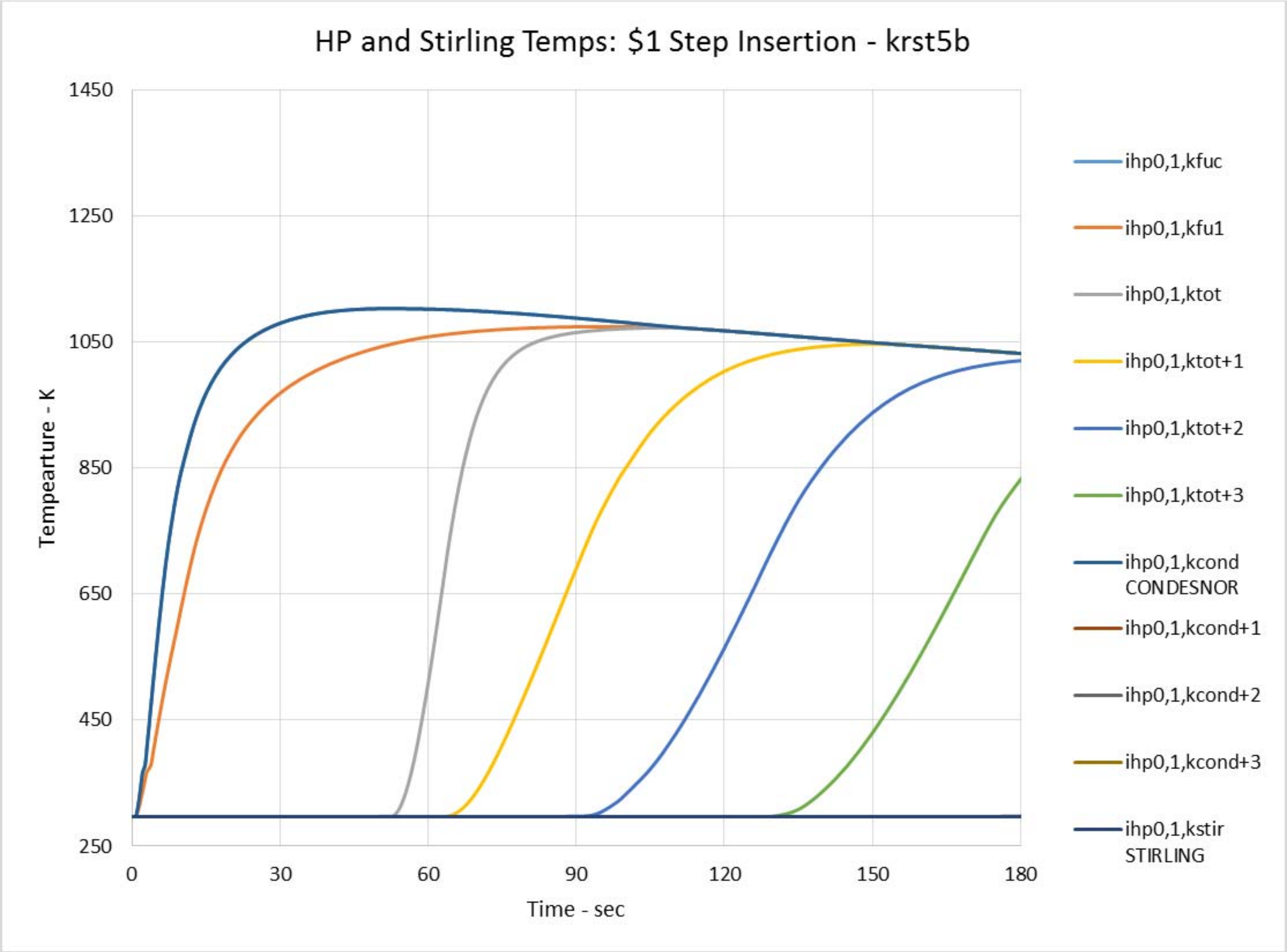
$1 Instantaneous



$1 Instantaneous

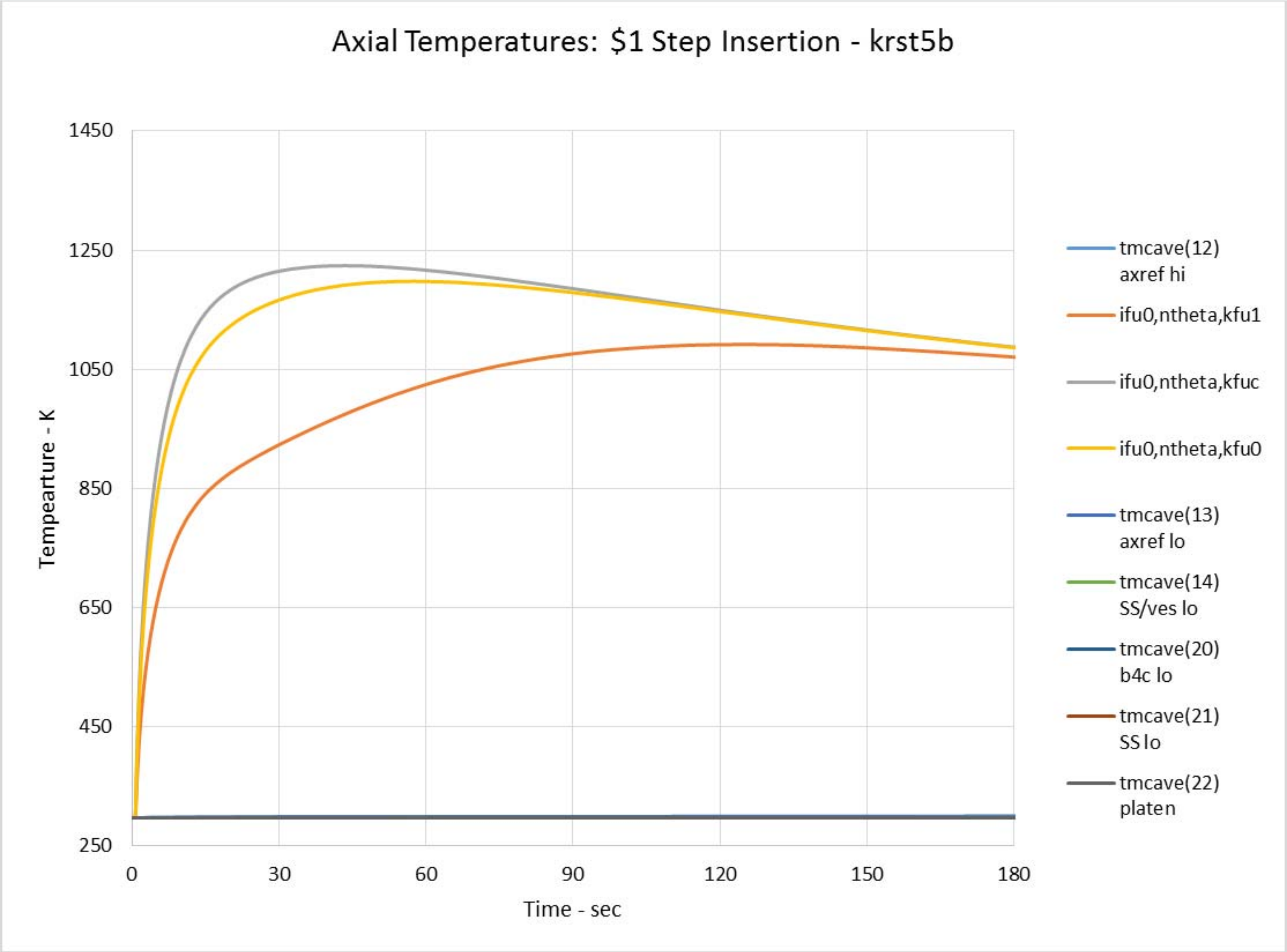


$1 Instantaneous

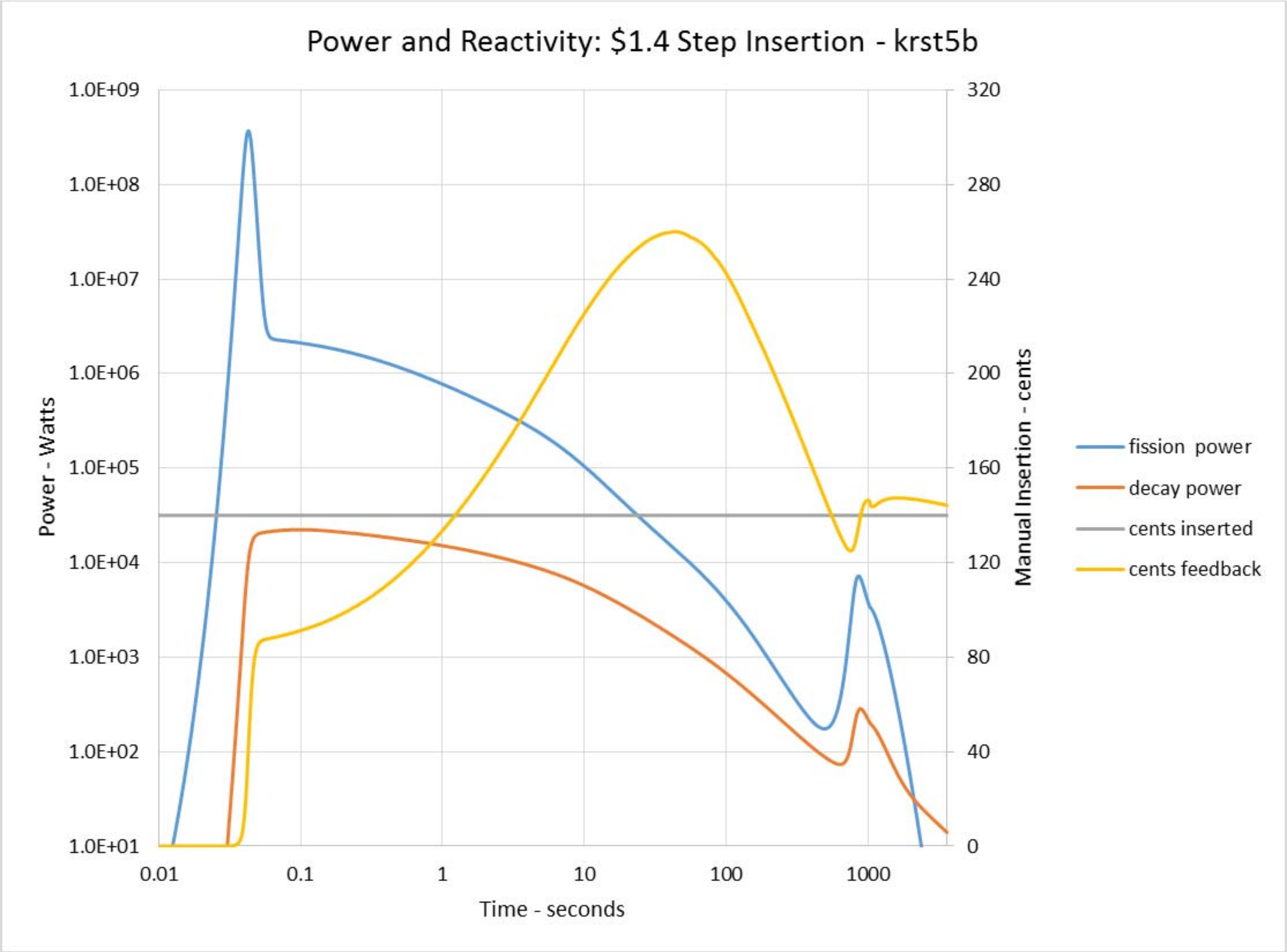


Heat pipes will not be this smooth!!

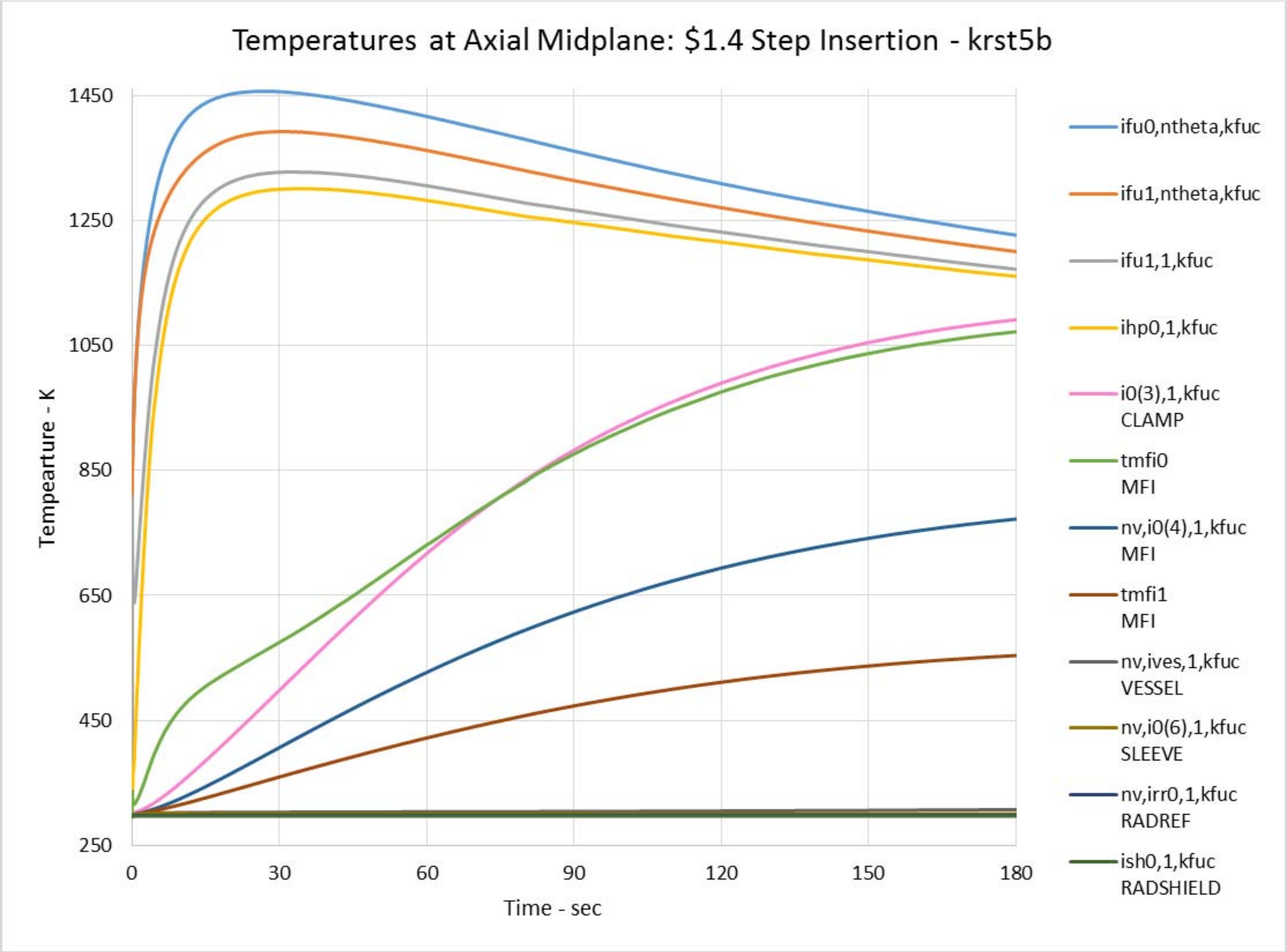
$1 Instantaneous



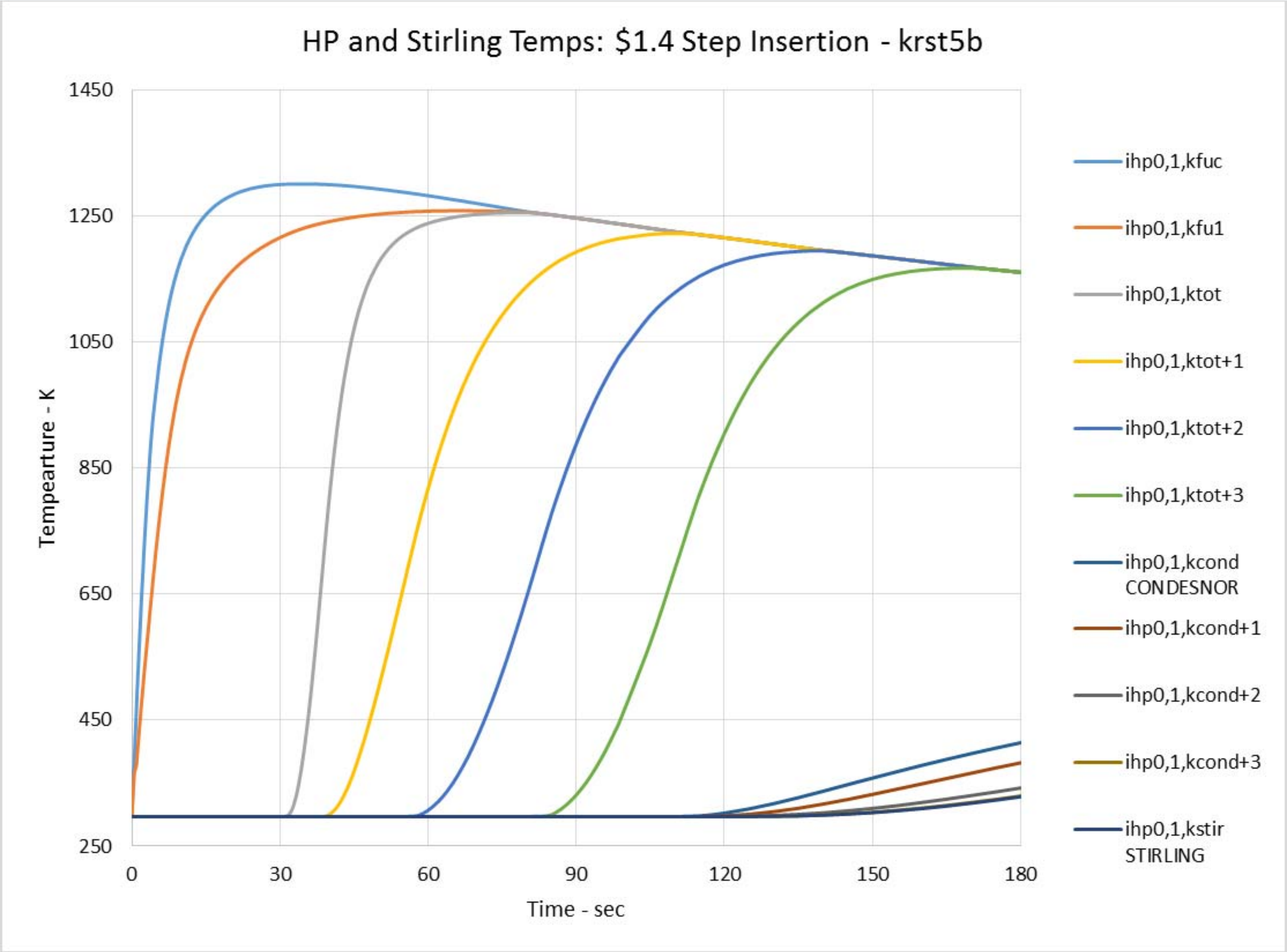
$1.4 Instantaneous



$1.4 Instantaneous

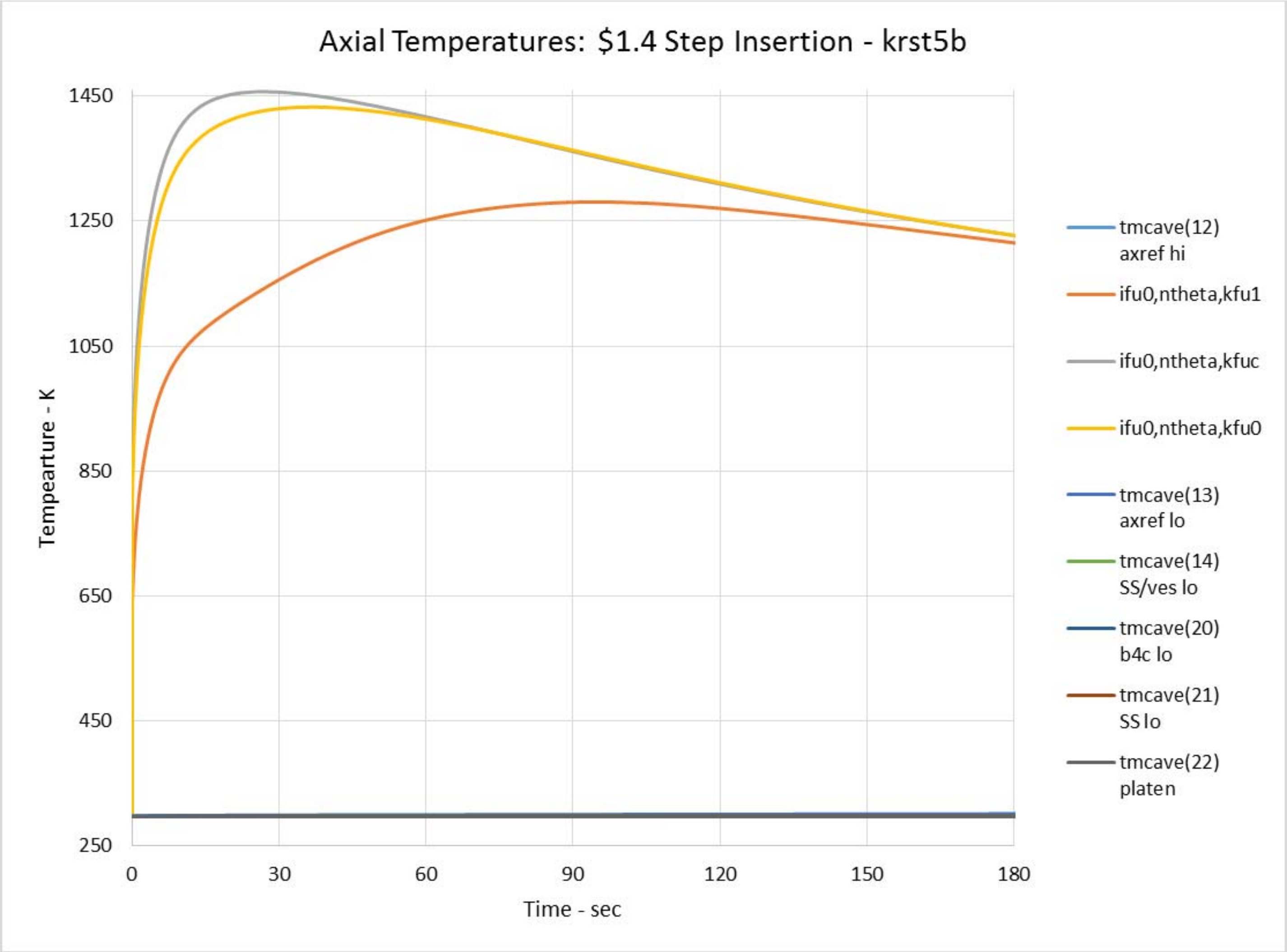


$1.4 Instantaneous



Heat pipes will not be this smooth!!

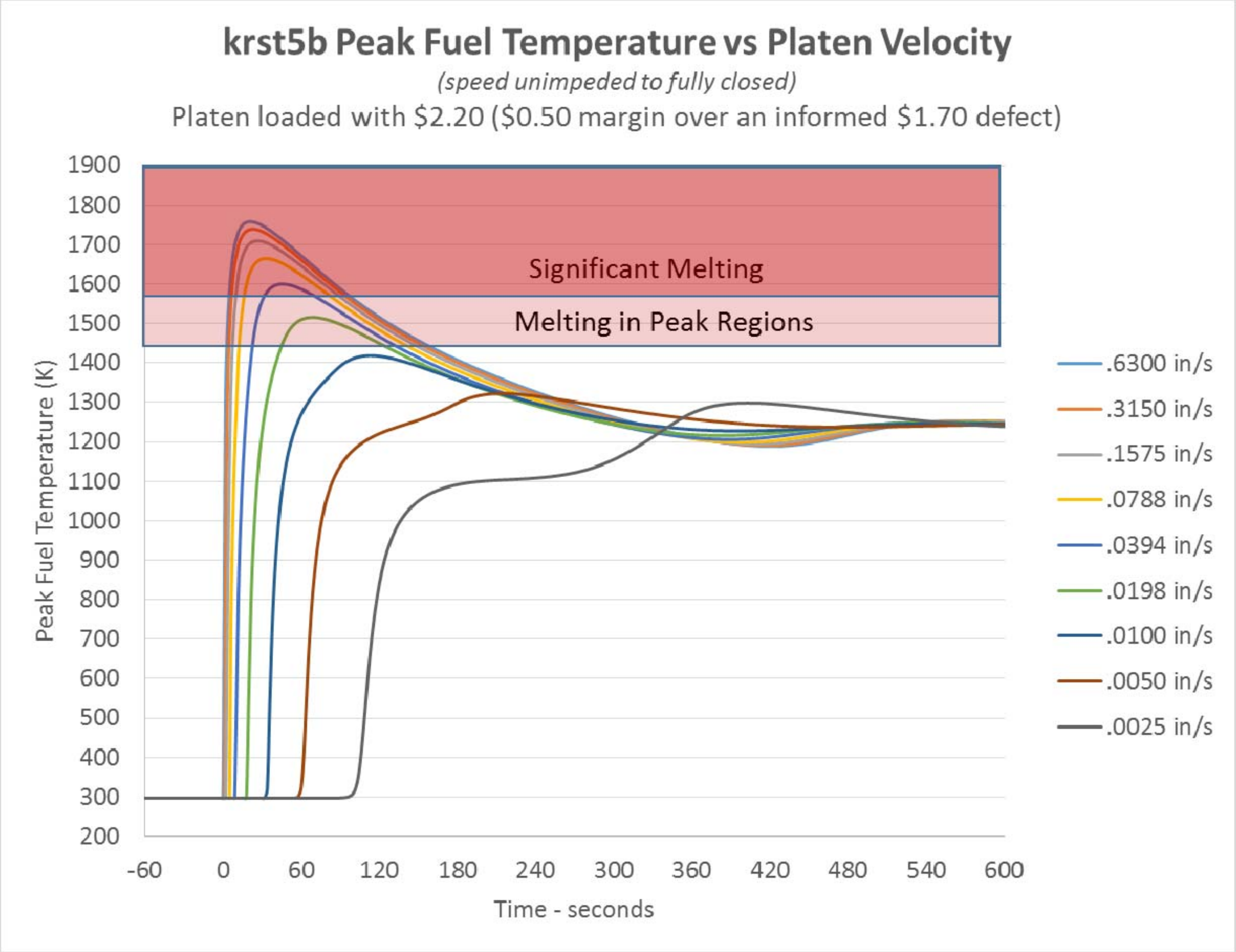
$1.4 Instantaneous



Effect of platen velocity in nominal and worst case scenario

- The following cases were run to determine what ramp speed would preclude fuel melt in this scenario
  - Knowing full well that the probability of a full-speed insertion to fully closed position is effectively zero.
    - Even with a major software/hardware glitch or human error caused this movement, automatic detector scram signals will occur, and if that for some reason fails, someone in the room will have time to manually scram.
- Two cases are presented
  - Nominal case: After analyzing the results of the previous testing, the operating defect is predicted to be $1.70 and the platen is loaded with 50 cents of margin.
  - Worst case assumptions: After analyzing the results of the previous testing, the operating defect is predicted to be $2.20 and the platen is loaded with 80 cents of margin (due to the discrete increments of BeO).
- Recall from previous slide…
  - 0.400 in/s up to 5” of closure
  - 0.200 in/s from 5” to 4” of closure
  - 0.100 in/s from 4” to 3” of closure
  - 0.050 in/s from 3” to 2” of closure
  - 0.032 in/s from 2” to 1.5” of closure
  - 0.016 in/s from 1.5” to 1” of closure
  - 0.008 in/s from 1” to 0.75” of closure
  - 0.004 in/s from 0.75” to 0.5” of closure
  - 0.002 in/s from .5” to 0.0” of closure
  - 0.001 in/s from 0.0” onward (like Zeus had it)
- The base case goes critical at ~0.8” and is at full temperature ~0.15”, and we should be able to load the machine for something similar to that after the crits. However, some cases might hit critical much sooner that 1”, depending on the configuration, especially the early crits without clamps/HPs. Thus I think it makes sense to slow down quite a bit when you’re within a few inches.

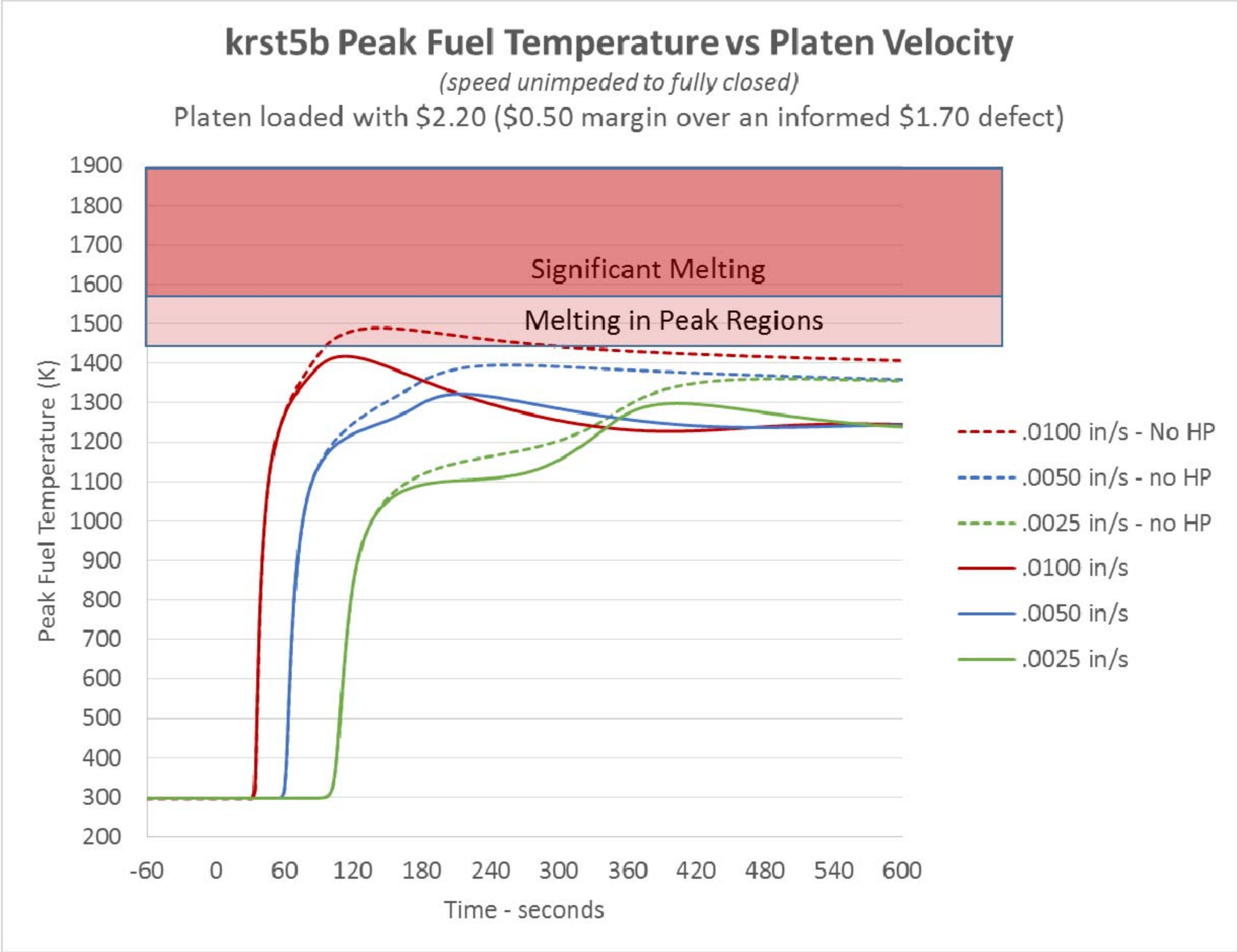
$2.20 Uninterrupted Full Insertion Scenarios



Uninterrupted full insertion represents worst-case scenario (for the modeled geometry/solution/source) and should be easy to deem incredible. For KRUSTY, COMET speed limited = .008 in/s when first critical, = .002 in/s when warm critical (when platen is within 0.5” of closing). The heat-up rates in all of these hypotheical cases would be “unhealthy” for the core – possible clamp failure, thermal shock within fuel, etc., but nothing energetic enough to damage vessel boundary.

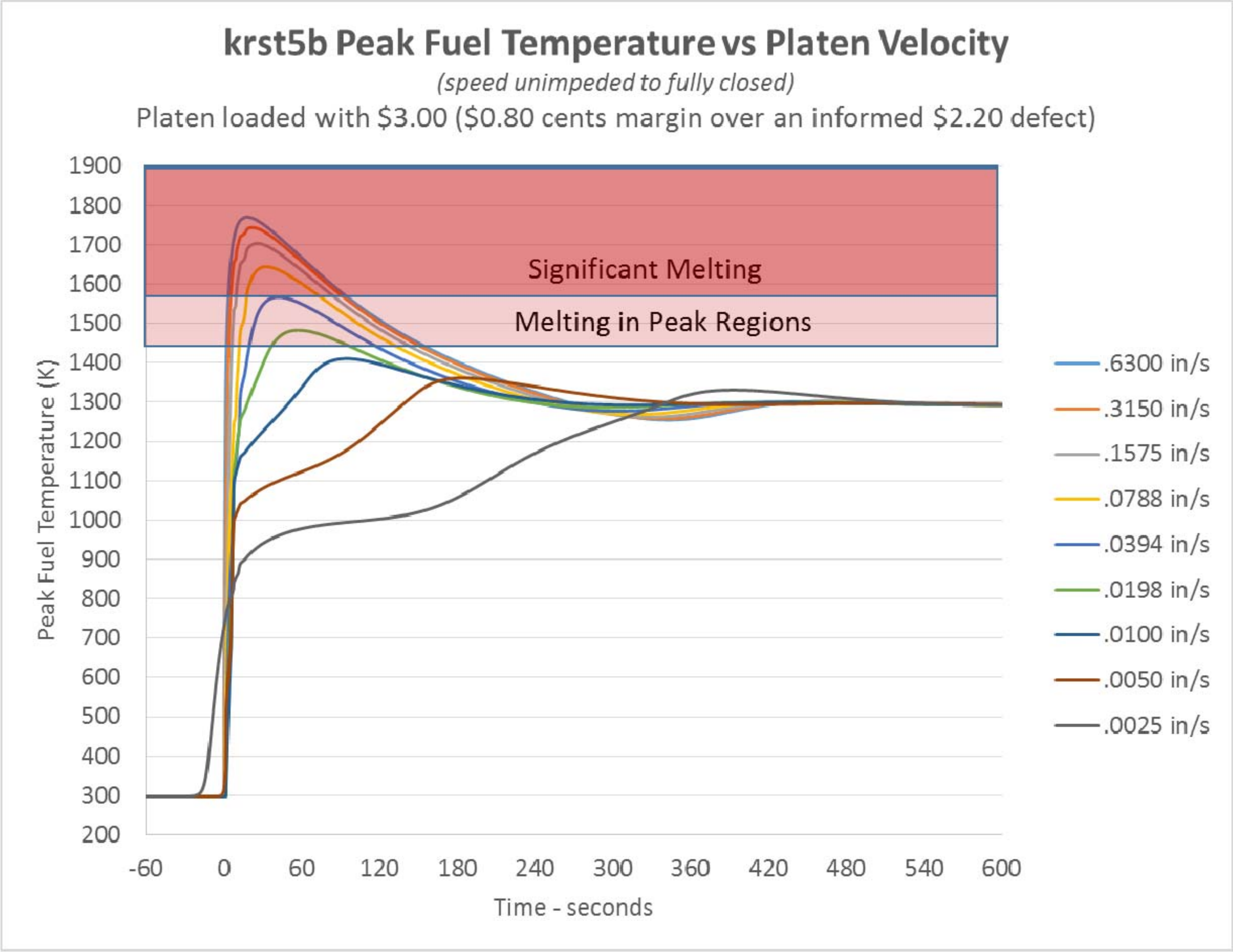
$2.20 Uninterrupted Full Insertion Scenarios

Dotted lines represent scenarios where heat pipes do not remove any heat



Heat pipe "operation" will likely be very ragged, but an assumption of no heat removal is extremely conservative (i.e. the fluid will boil, splash, etc. in one manner or another, which will indeed move heat out of the core).

$3.00 Uninterrupted Full Insertion Scenarios



This case assumes that the initial testing has indicated an operating reactivity defect of $2.20 (as opposed to the current nominal model prediction of $1.70). On top of that, $0.80 of margin is loaded, i.e. the worst case “discrete” loading to get at least $0.50. Even though the loading is much greater than the previous case, the actual higher feedback of the system dampens the transient. Again, the heat-up rates are likely high enough to damage core, but the probability of these scenarios is essentially zero.

Bottom line of safety calculations

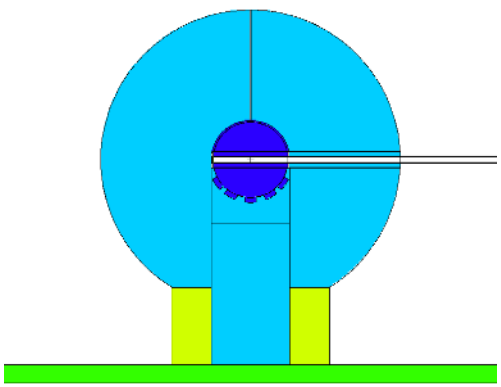
- There are 3 scenarios that could cause fuel melt
  - Step insertion (uninitiated)
    - Baseline (zero bias) model shows possible onset of partial melt in peak regions at ~$1.40.
  - Rapid initiated reactivity insertion
    - Baseline model shows possible onset of partial melt at ~$2.20 cents at max platen speed between .01 in/s and .02 in/s
    - Full melting at ~.05 in/s
      - Note, these scenarios closes platen fully, to a level with more reactivity than is needed to reach nominal power.
  - Inserting too much reactivity regardless of speed
    - Baseline model shows onset of partial melt at ~$2.75
      - Data is in slide "Fuel Temperature Worth
    - The predicted magnitude of this number could change significantly based on the results of the warm-crits.
- Fuel melt will be a major facility headache, but source term low and release low probability.
- Based on modeling and past experience, there is no credible loading (even assuming extreme worst-case modeling biases) that could cause vessel damage during a step insertion.

Melting Consequences

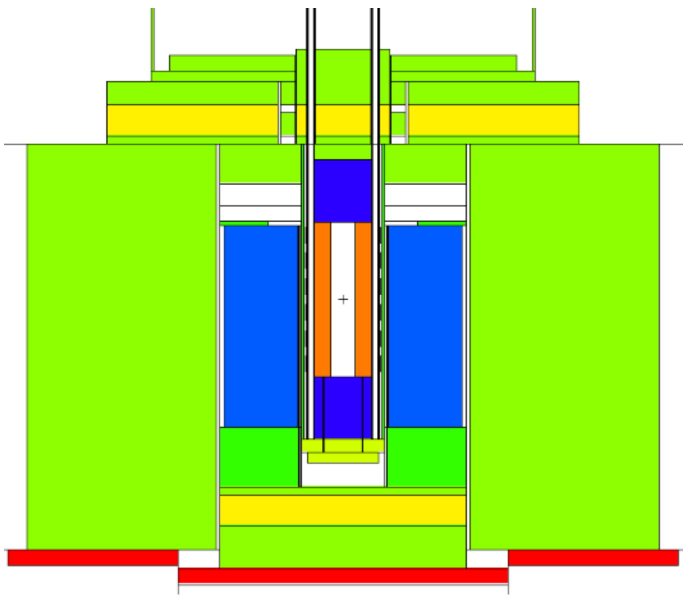
- Any partial melting will lower reactivity
  - Melting will occur in the highest worth region of the reactor (i.e. the axial centerline), and flow towards to bottom of core will lower reactivity.
  - This will provide negative feedback and prevent/mitigate any further melting.
- If for some reason near total/bulk fuel melt were to occur (essentially impossible) recasting might raise or lower reactivity depending on the configuration and assumptions.
  - Configurations can be speculated where fuel could re-solidify/recast into a more reactive geometry.
  - However, it is impossible to speculate a scenario where a full melt and worst-case recast will be critical if the platen is sufficiently withdrawn (i.e. without sufficient BeO reflection)
    - The platen "handcrank" position is sufficiently low to ensure subcriticality in the worst possible melt/recast scenario.
  - Going to the absolute extreme, even if someone tried as hard as they could to create a problem and assumed the worst at every turn, and the fuel totally melted into a critical configuration, the reactor would only operate at low power until enough U evaporated (boiling or simply to replenish vapor pressure) and condensed on chamber or other materials outside of core. The vessel can maintain integrity to temperature substantially higher than fuel melting point, so everything still contained.
- Most importantly, the previous results have shown that there is no realistic scenario for any fuel melting, i.e. 1) too much reactivity is improperly loaded on the machine and 2) the platen is accidentally fully inserted at a rate higher than it is supposedly limited to.

Room radiation environment during operation

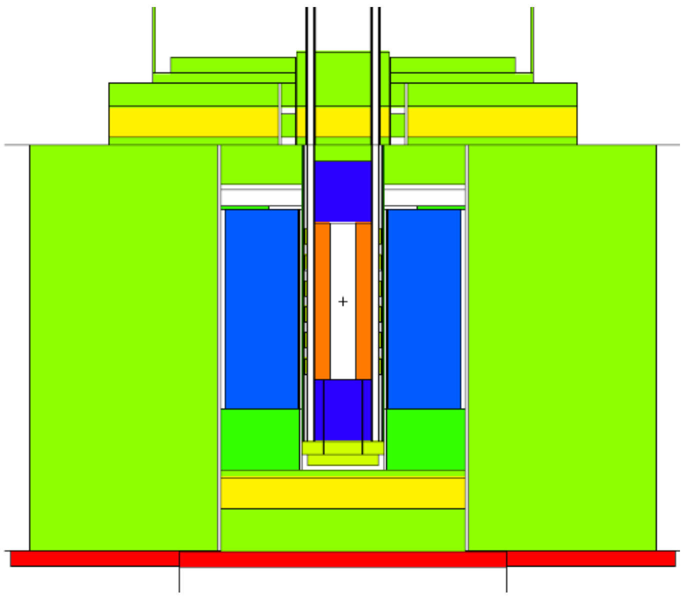
DUFF



Nominal KRUSTY
Room Temperature
Short-stack = 2.54 cm
Ztable = -3.05 cm



Nominal KRUSTY
Operating Temperature
Short-stack = 2.54 cm
Ztable = 0.00 cm



Approximately to scale: Flattop reflector OD is 48 cm, KRUSTY radial OD is 38 cm

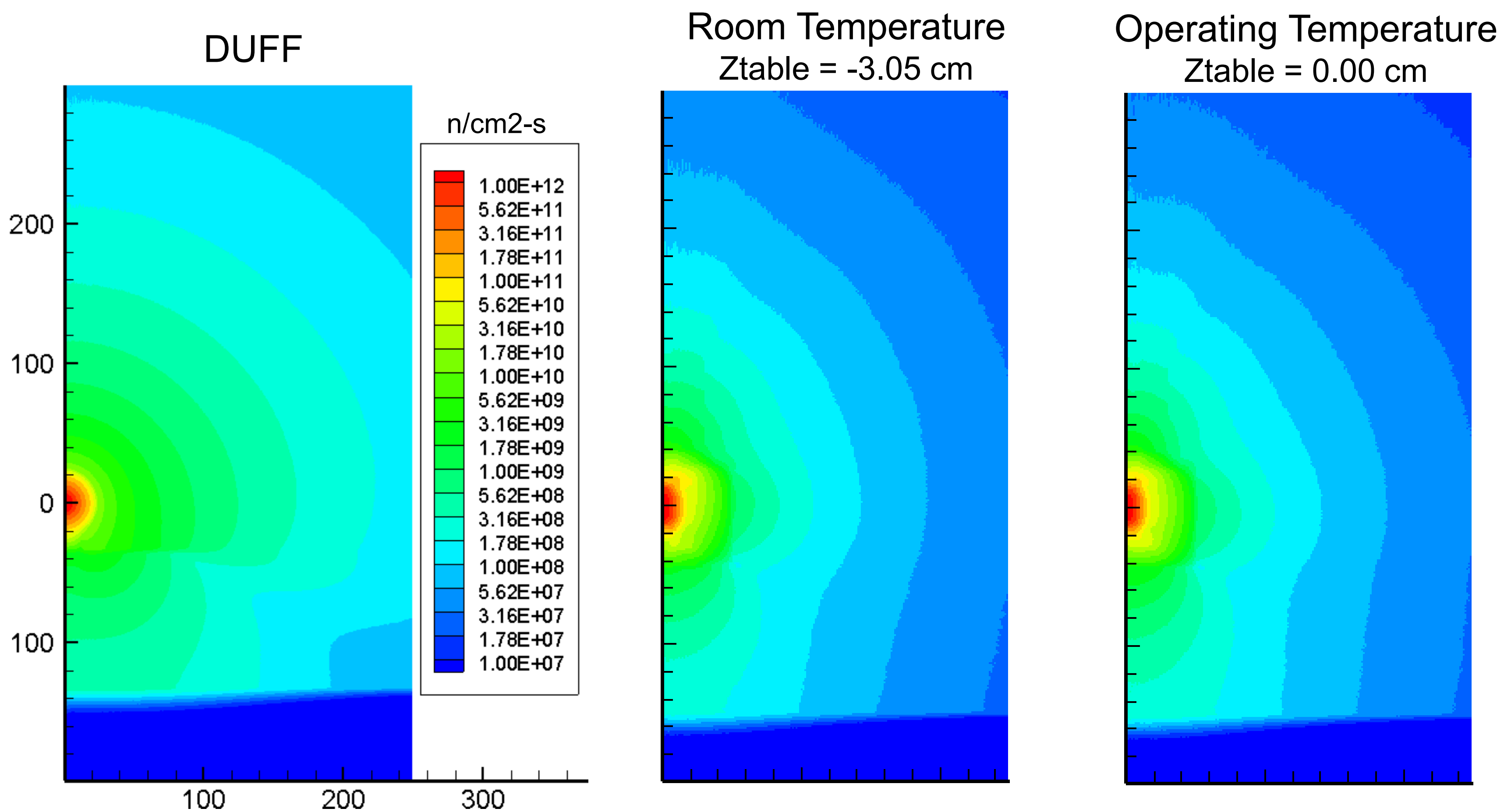
KRUSTY Room Activation

- Goal is to keep room activation (neutron fluence) for a KRUSTY run in the same ballpark as DUFF run.
  - At least within order of magnitude, and hopefully closer to a factor of 2, but the ability to substantially reducing room fluence was hampered by axial clearance issues and to a lesser extent mass concerns.
- DUFF runs were rather short.
  - DUFF Test#1 operated 1.3 kWh
  - DUFF Test#2 operated 2.0 kWh
    - Flattop Free Runs <~1 kWh
- The proposed KRUSTY campaign contains 3 short low-temperature tests and one 24 hr+ run
  - The energy of the entire campaign is calculated as ~80 kWh
    - Therefore, KRUSTY is expected to have 75/3.3 or ~20 times more fissions than DUFF, so it was designed to be more effective at shielding neutrons.
- Note that "room activation" is not the limiter of room re-entry; rather, it is the activation of the nuclear assembly itself.
  - Shielding from the activated experiment is wee mitigated by the shield, as long as the platen has been hand cranked so that the reflector is left partially inserted after experiment is completed.
  - The reason to prevent room activation is the potential to create background radioactive noise for sensitive experiments in the future.

DUFF vs KRUSTY: Neutron Flux >100 keV

NEEDS UPDATE
But no significant change expected

4 kWt, Nominal Model, BeO short-stack = 2.54 cm



The room fast neutron flux from KRUSTY is ~4x lower than DUFF; slightly more then 4x radially, and slightly less than 4x above and below.

The flux above the reactor is ~10% higher when the system is operating cold, because the BeO stack is not filling the gap in the upper corners.

DUFF vs KRUSTY : Gamma Dose Rate (Rad-Si/hr)

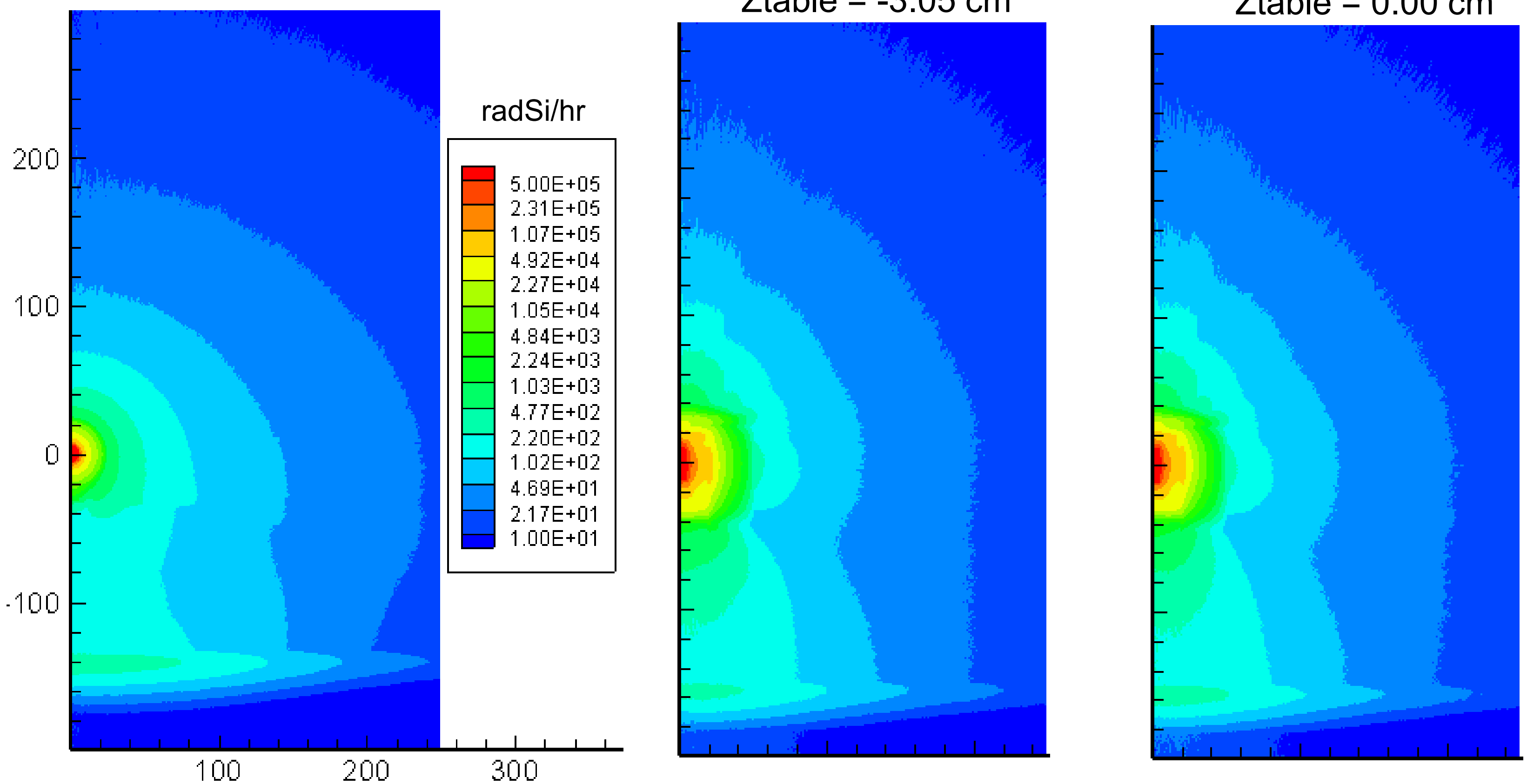
NEEDS UPDATE
But no significant change expected

4 kWt, Nominal Model, BeO short-stack = 2.54 cm

DUFF

Room Temperature
Ztable = -3.05 cm

Operating Temperature
Ztable = 0.00 cm

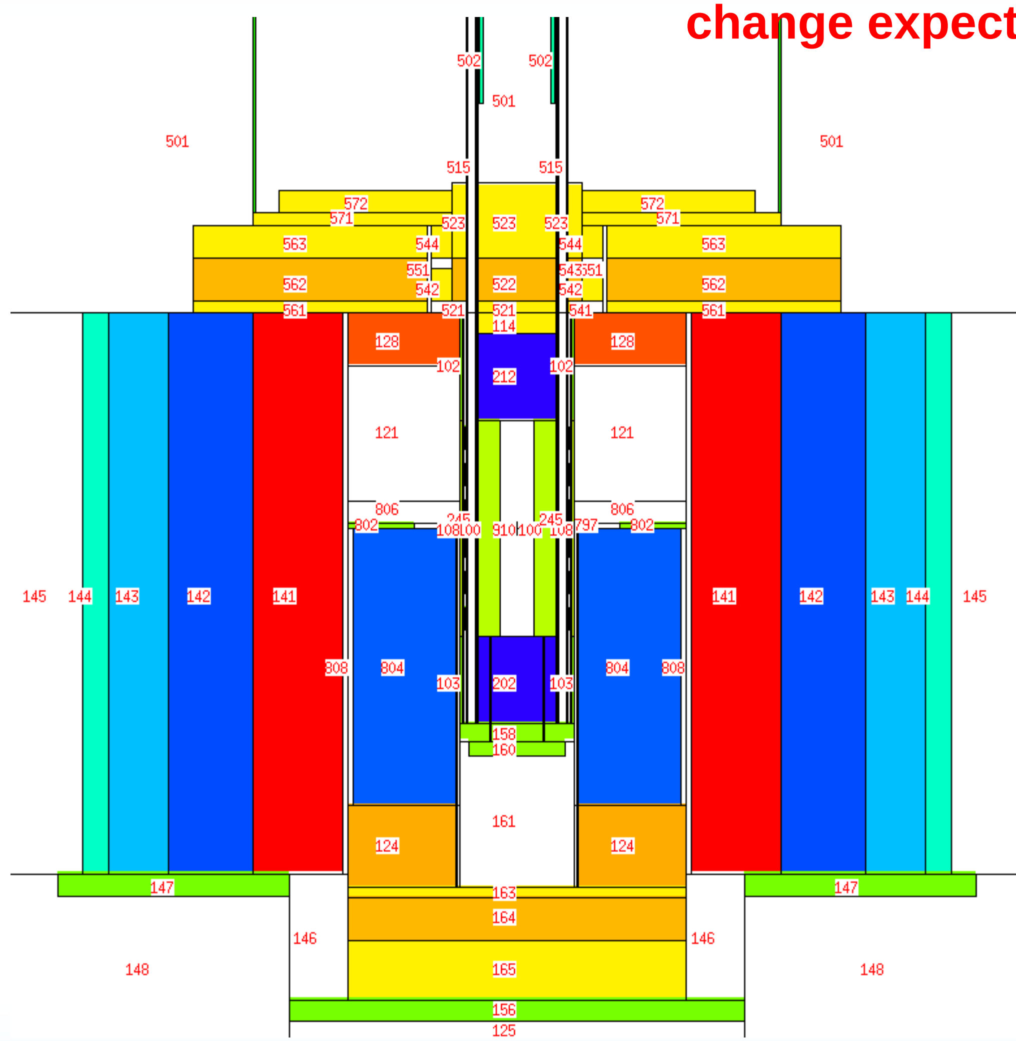


The gamma dose rate slightly lower than DUFF in the radial direction and below, and higher above the reactor. Additional shielding and/or the B4C collar could help if desired, but integral gamma dose should not be an issue regardless.

Activation Calculations

NEEDS UPDATE
But no significant change expected

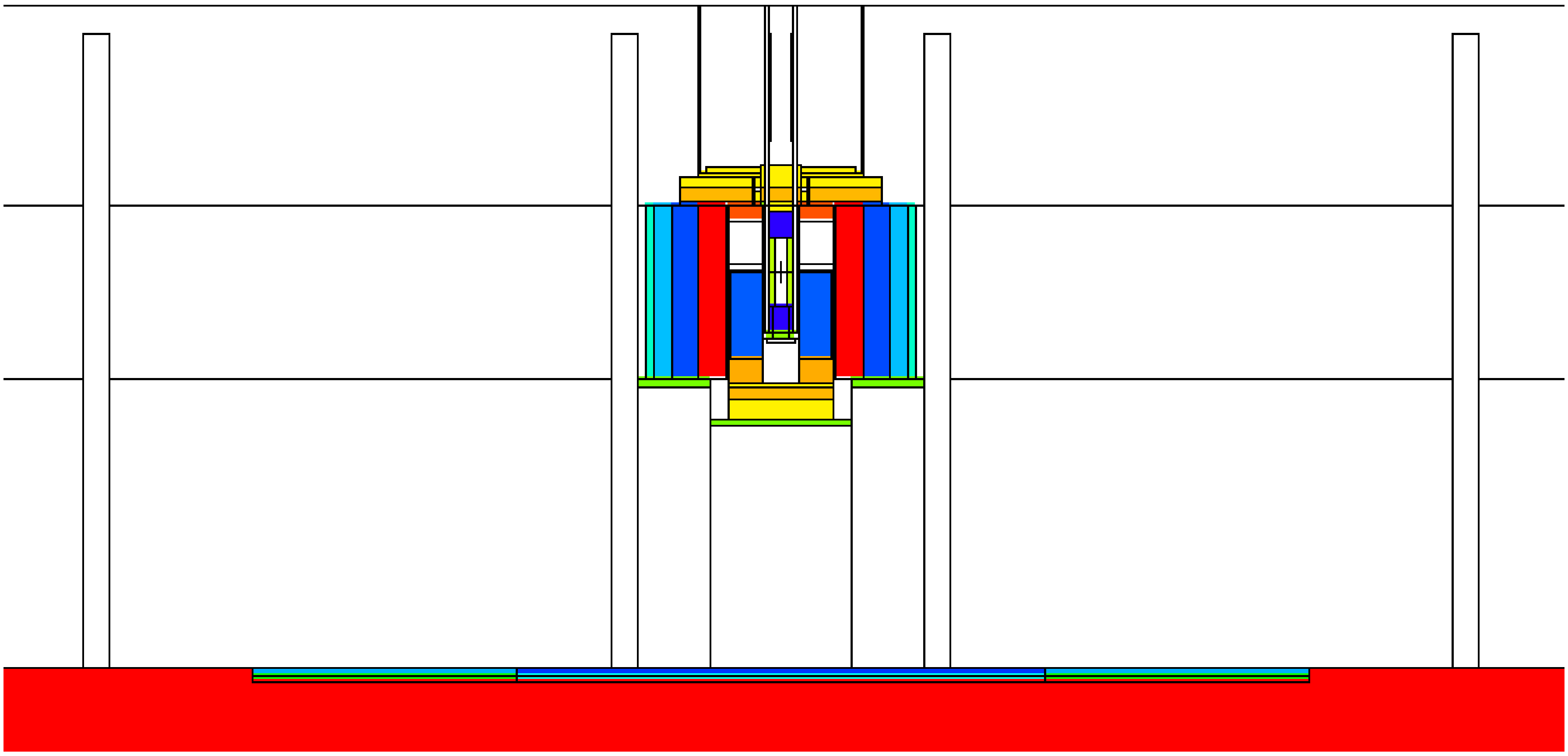
	Activation Calculations		
		cell	volume
1	fuel	100	1971.1
2	core vessel	108	323.43
3	wagon wheel	124	10717
4	upper wheel	128	6965
5	in rad shield	141	112281
6	mid rad shield	142	149423
7	mid rad shield	143	129292
8	out rad shield	144	61074
9	core HP	242	69.46
10	PCS HP	512	163.92
11	PCS ves	573	3904
12	Mar-M cylinder (5kg)	502	641
13	Floor:top-mid	136	78540
14	Floor:top-out	137	235619
15	Floor:mid-mid	138	78540
16	Floor:mid-out	139	235619



Activation and gamma source calculated at each time step for each component listed

Floor Regions and Volume Tally Locations

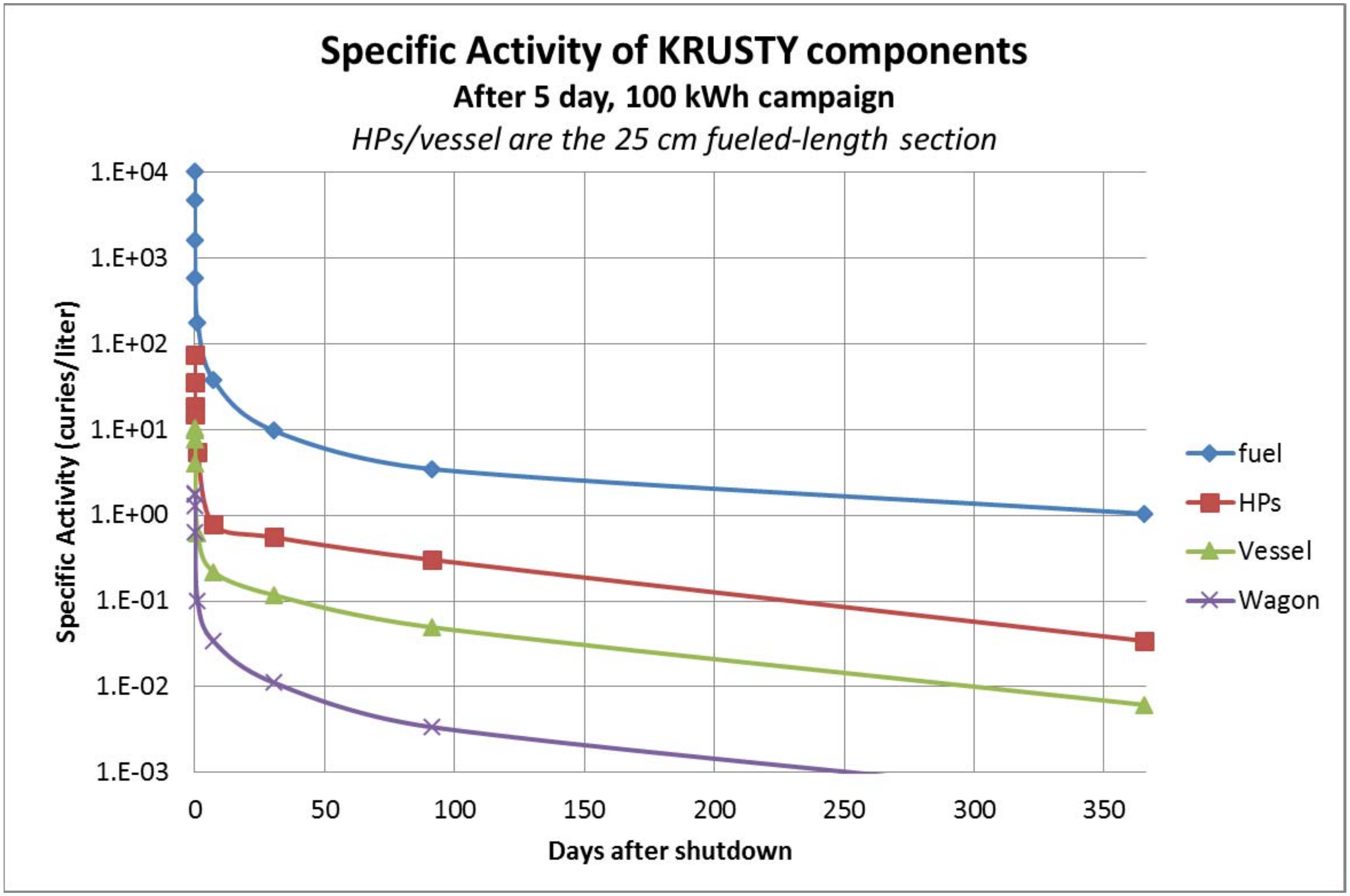
NEEDS UPDATE
But no significant change expected



Floor tallies further out and deeper should be insignificant, or at least can be estimated by extrapolation from the current ones (top 1” and next 1”, 1 m and 2 m radius)

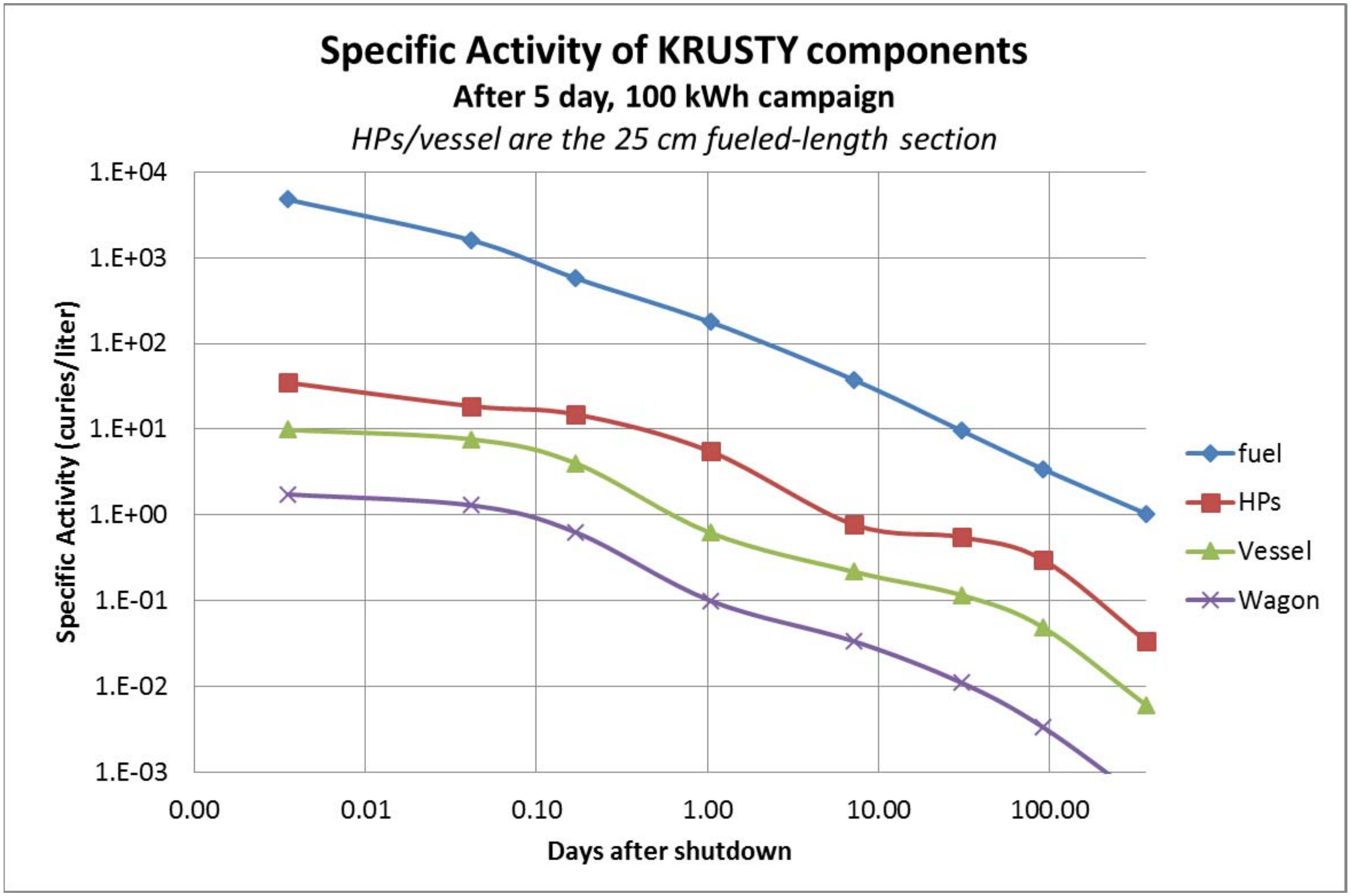
Vertical columns are location of volume tallies to approximate humans (they will be split into 4 60 cm axial slices).

KRUSTY Activation



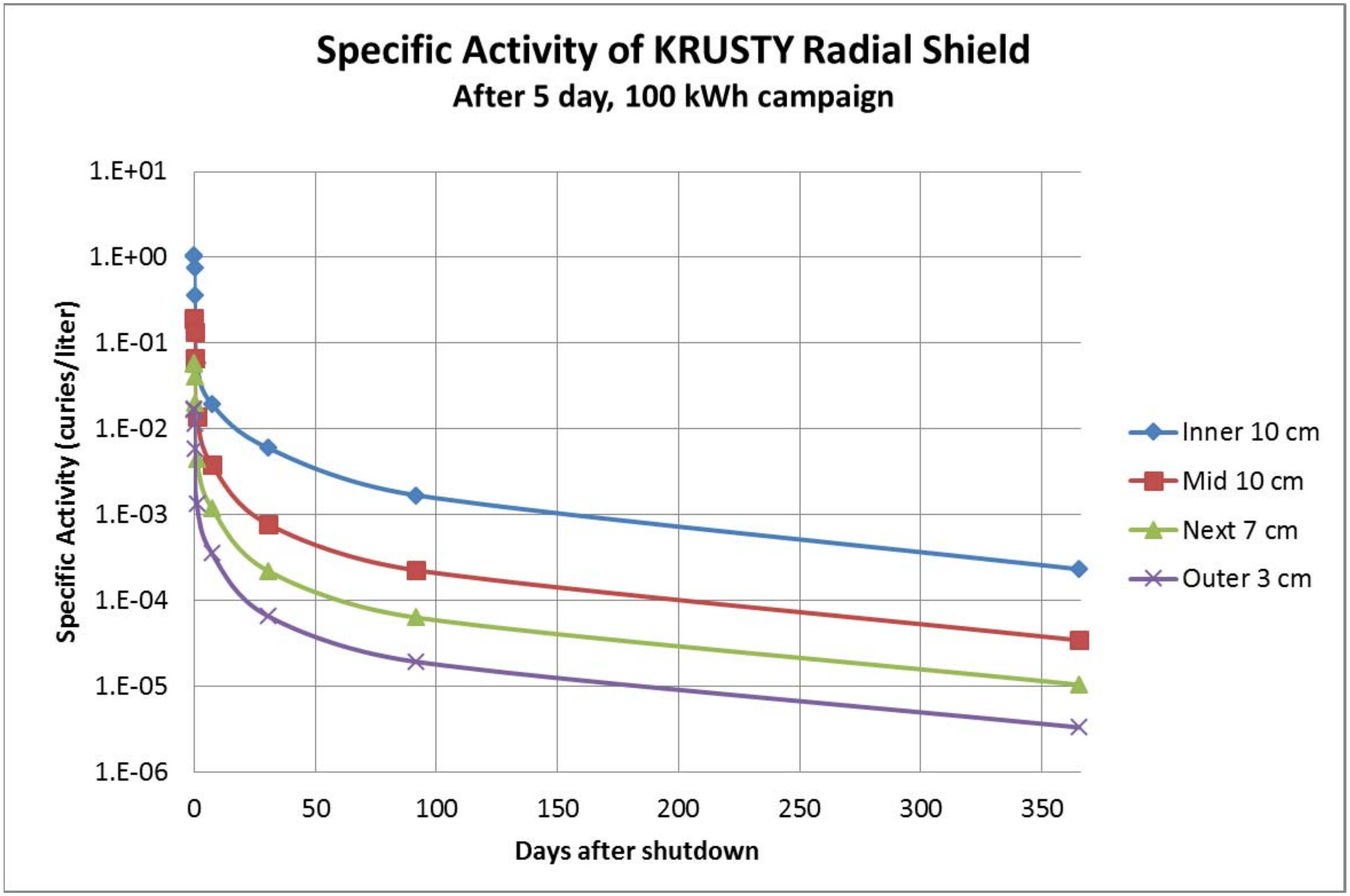
NEEDS UPDATE: No significant change in trends expected, except that the proposed KRUSTY campaign will have lower burnup (80 kWhr as opposed to 100 kWhr above)

KRUSTY Activation



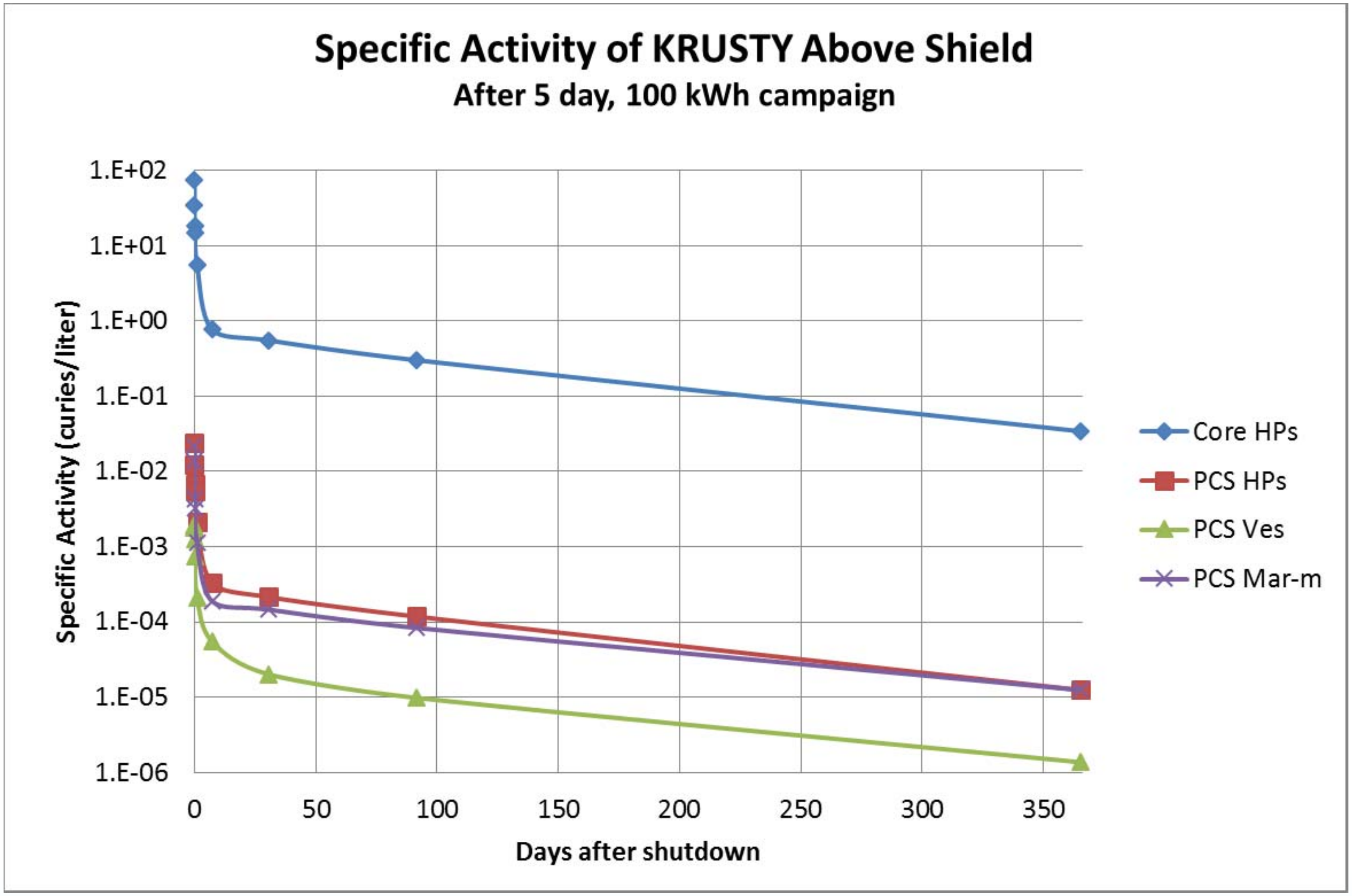
NEEDS UPDATE: No significant change in trends expected, except that the proposed KRUSTY campaign will have lower burnup (80 kWhr as opposed to 100 kWhr above)

KRUSTY Activation



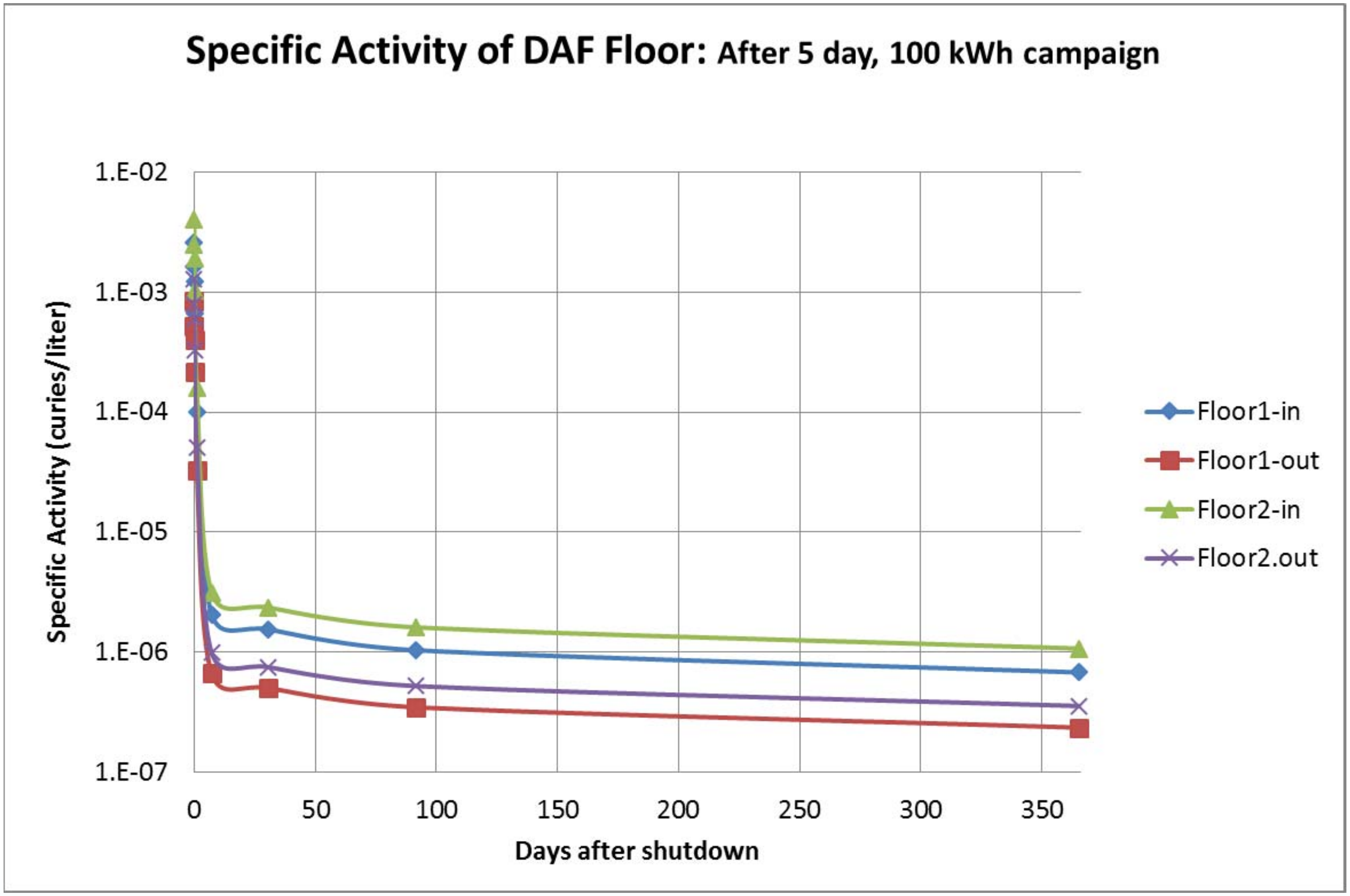
NEEDS UPDATE: No significant change in trends expected, except that the proposed KRUSTY campaign will have lower burnup (80 kWhr as opposed to 100 kWhr above)

KRUSTY Activation



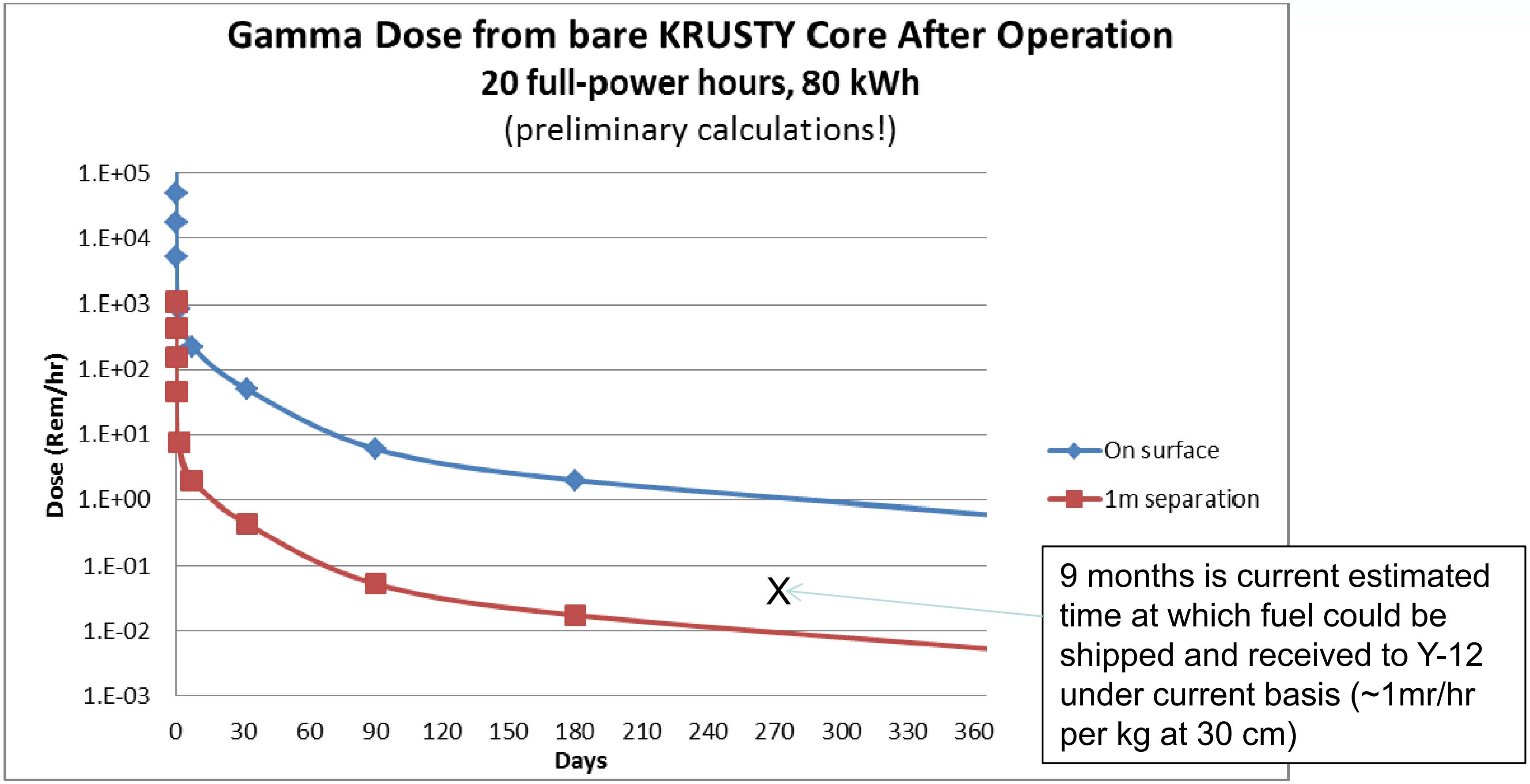
NEEDS UPDATE: No significant change in trends expected, except that the proposed KRUSTY campaign will have lower burnup (80 kWhr as opposed to 100 kWhr above)

KRUSTY Activation



NEEDS UPDATE: No significant change in trends expected, except that the proposed KRUSTY campaign will have lower burnup (80 kWhr as opposed to 100 kWhr above)

Gamma Dose Rate vs Time

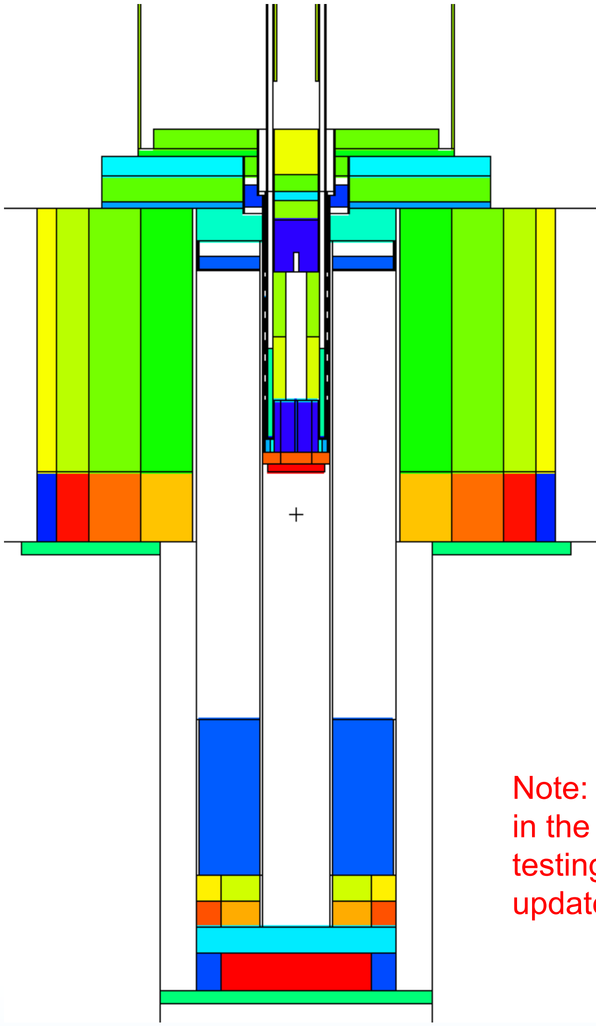


Most of the dose after 30 days is from gammas of energy <1 MeV, which are effectively shielding by thin layer of high-Z material.

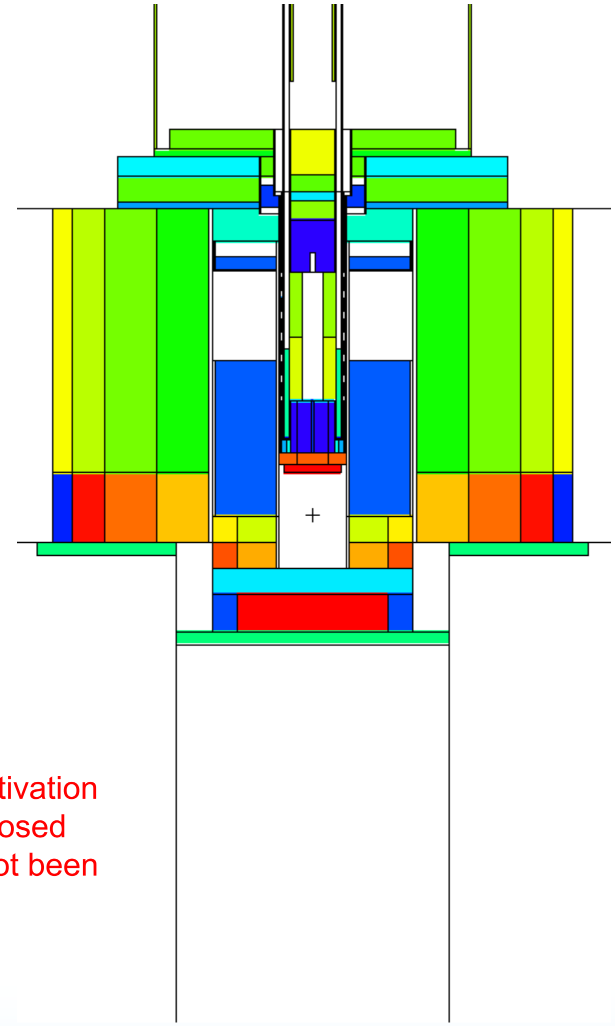
NEEDS UPDATE: No significant change in trends expected, except that the proposed KRUSTY campaign will have lower burnup (80 kWhr as opposed to 100 kWhr above)

Dose After Operation – MCNP model

Fully withdrawn/Loading



Hand-cranked/Stowed

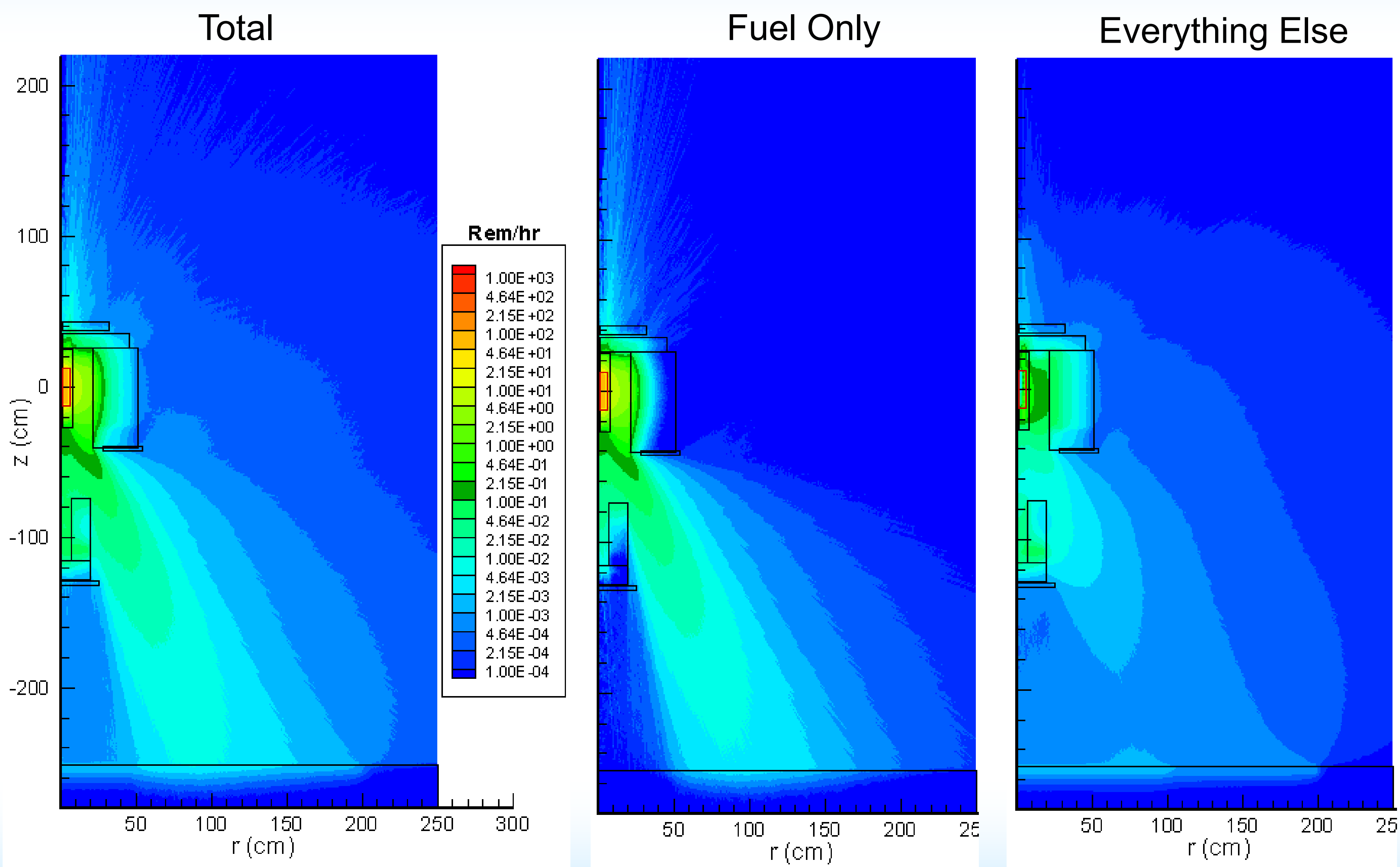


Each color represents a unique MCNP region for which activation was calculated via MONTEBURNS and a gamma source was calculated by MAGGIE. The transported dose from each individual component (and the sum of the components) is shown on the following slides.

Note: The following calcs indeed use the activation in the updated “shim-stack” model and proposed testing, whereas the previous slides have not been updated to the newer results yet.

The fully withdrawn platen leaves a large gap for core radiation to escape. This will be the position of the platen for loading and all zero-power criticals and low-temperature testing. For the final-run, the platen will be hand-cranked to the “stowed” position on the right, which substantially reduces the dose in the room until KRUSTY has cooled enough for removal from Comet.

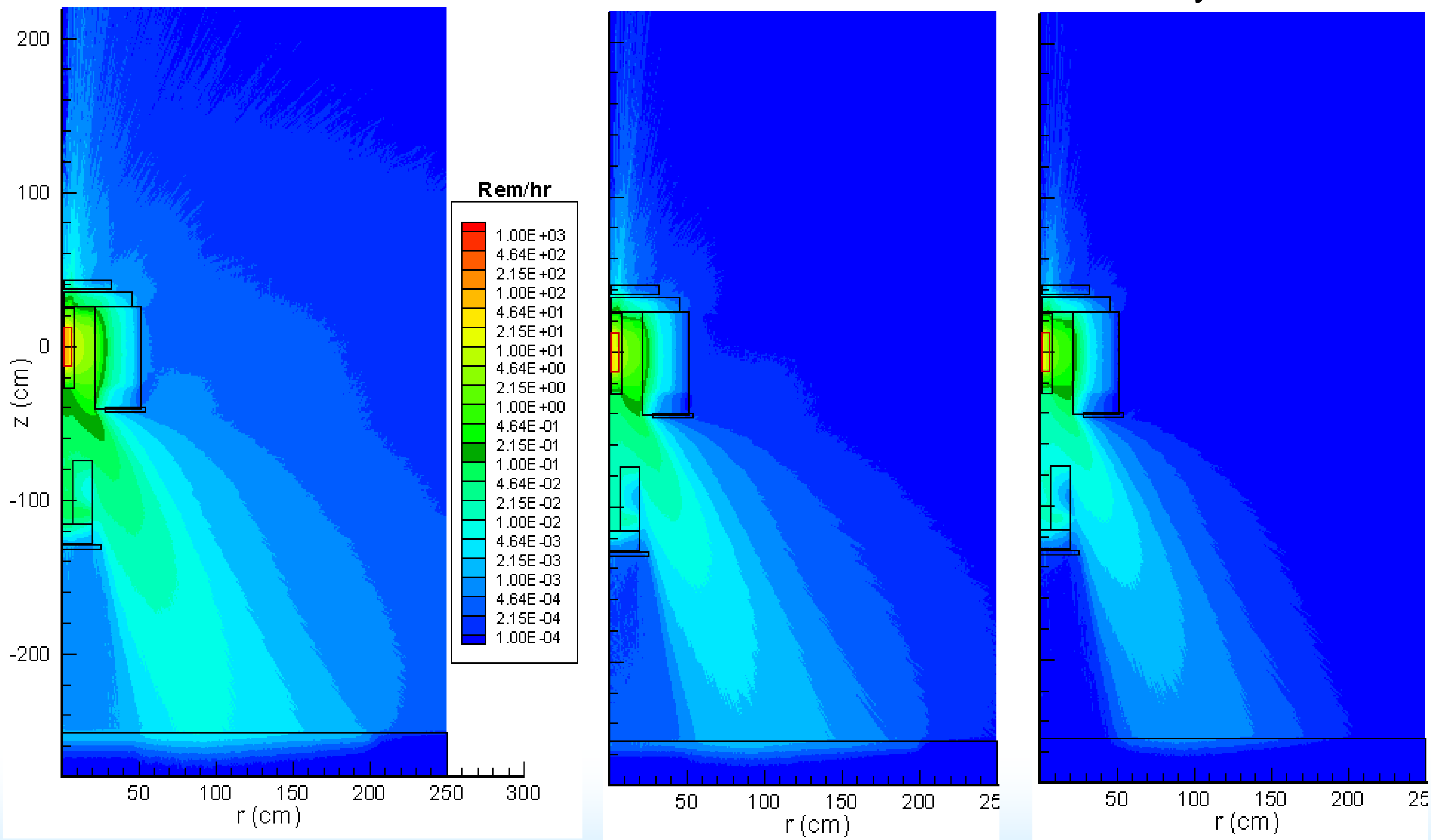
Gamma dose 1 day after 20 cent free run
(note: revised plan is for 15 cents)



Dark green (>100 mRem/hr) added to make countours easier to read

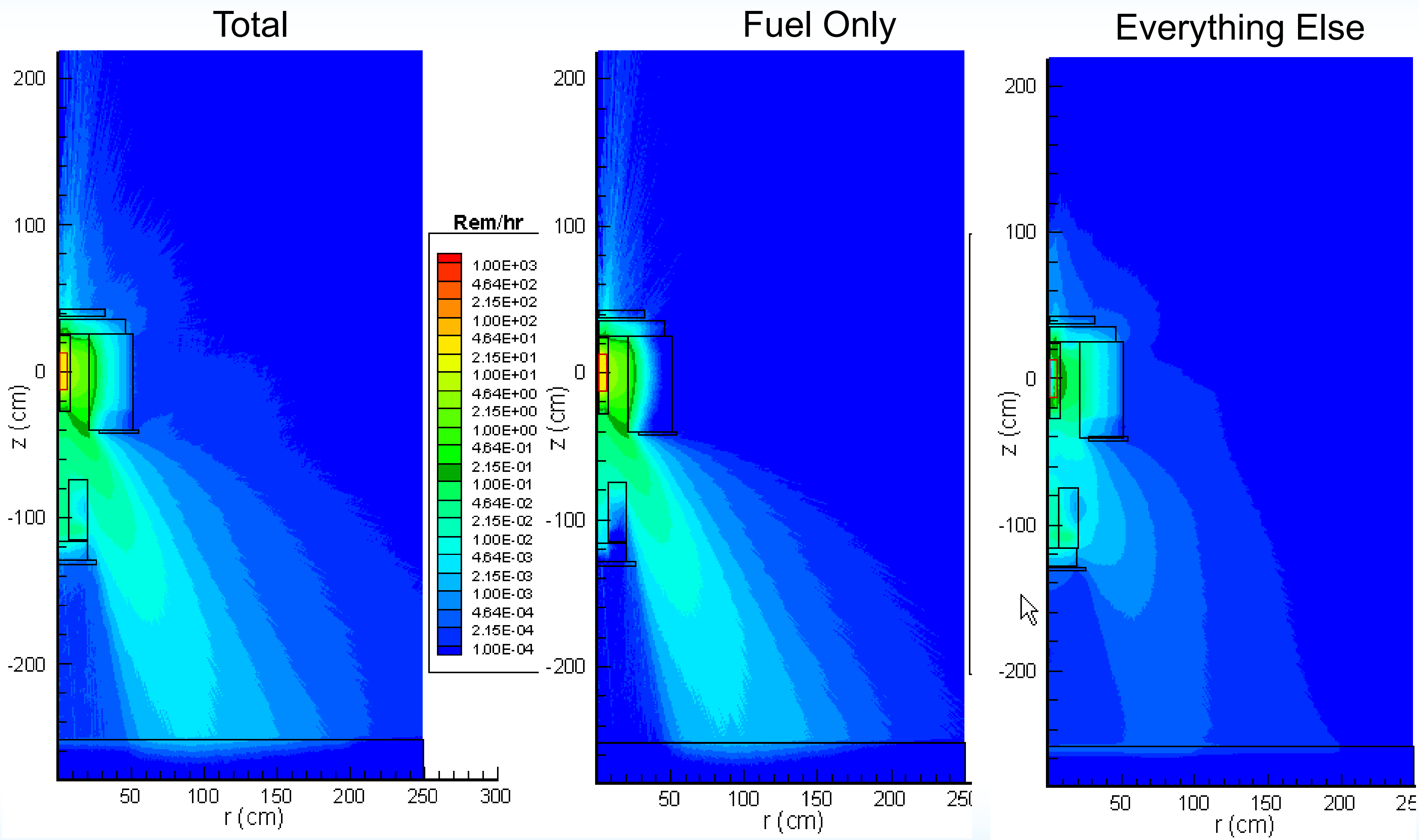
Gamma dose after 20 cent free run
(note revised plan is for 15 cents)

1 day later | 2 days later | 4 days later



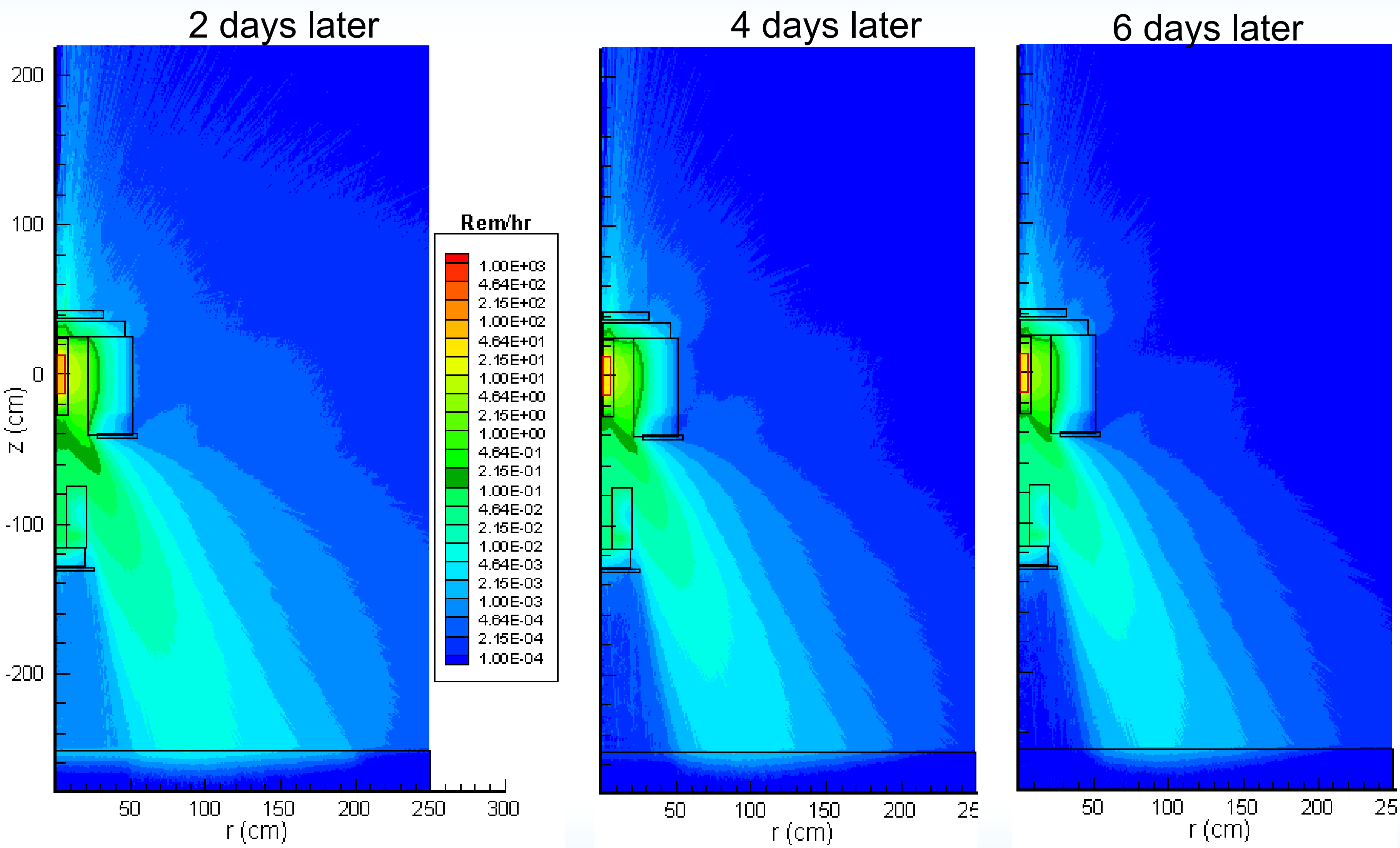
2 days selected as baseline, then perform 40 (revised 30) cent burn

Gamma dose 3 days after 40 cent run
Note: revised plan if for 30 cents



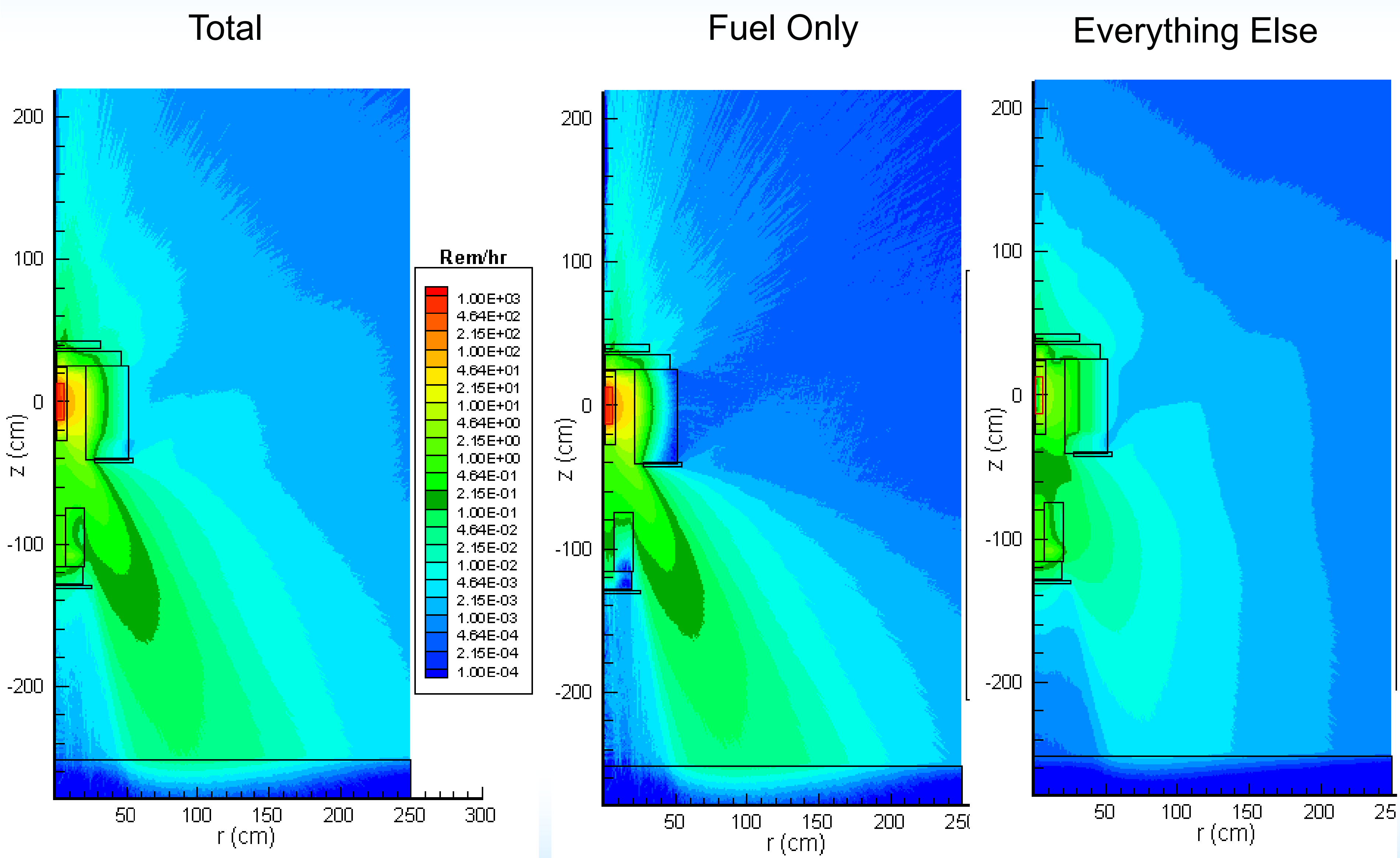
Dark green (>100 mRem/hr) added to make countours easier to read

Gamma dose after 60 cent run

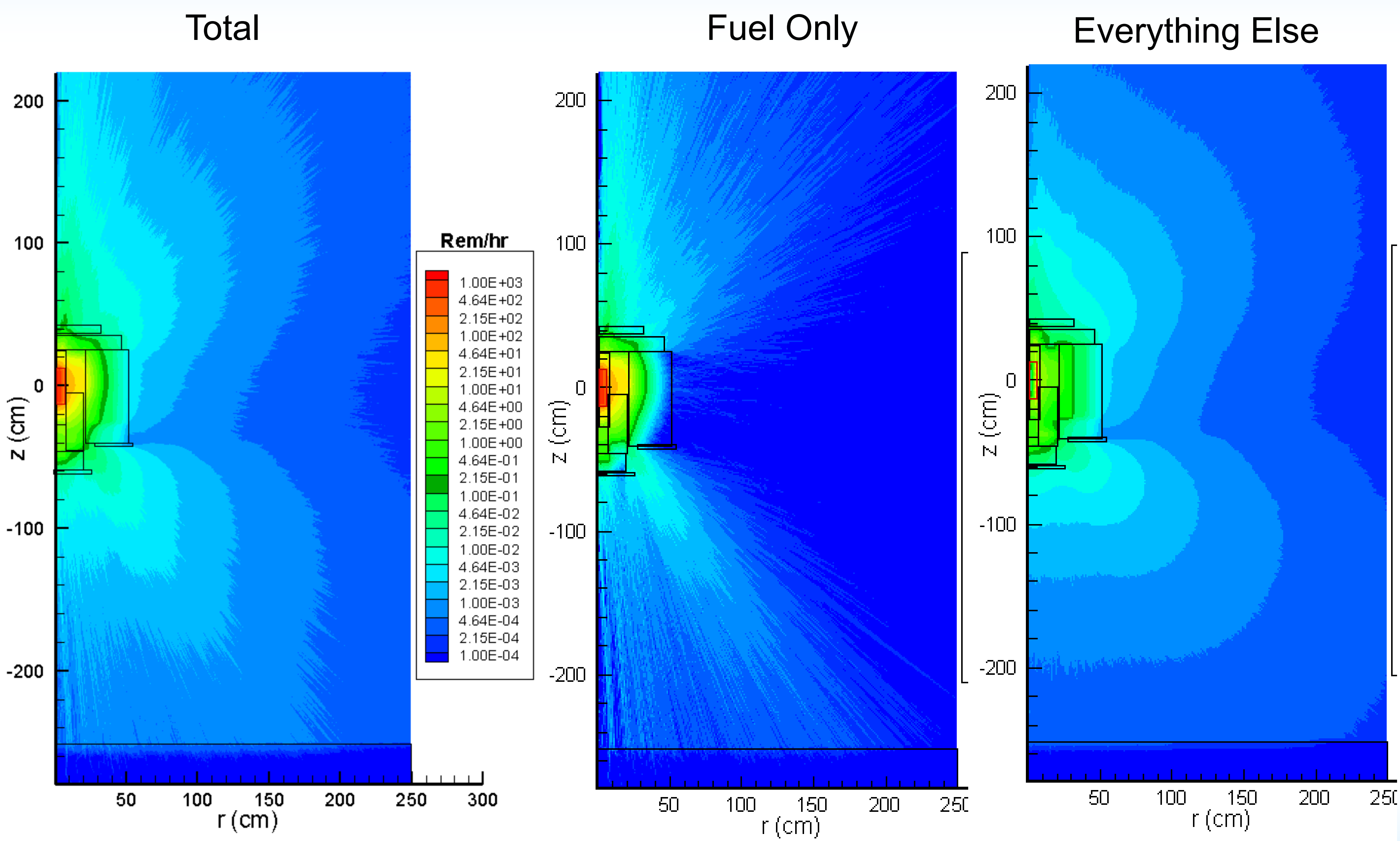


6 days selected as baseline, then perform final run

Final Run: 16 day decay withdrawn

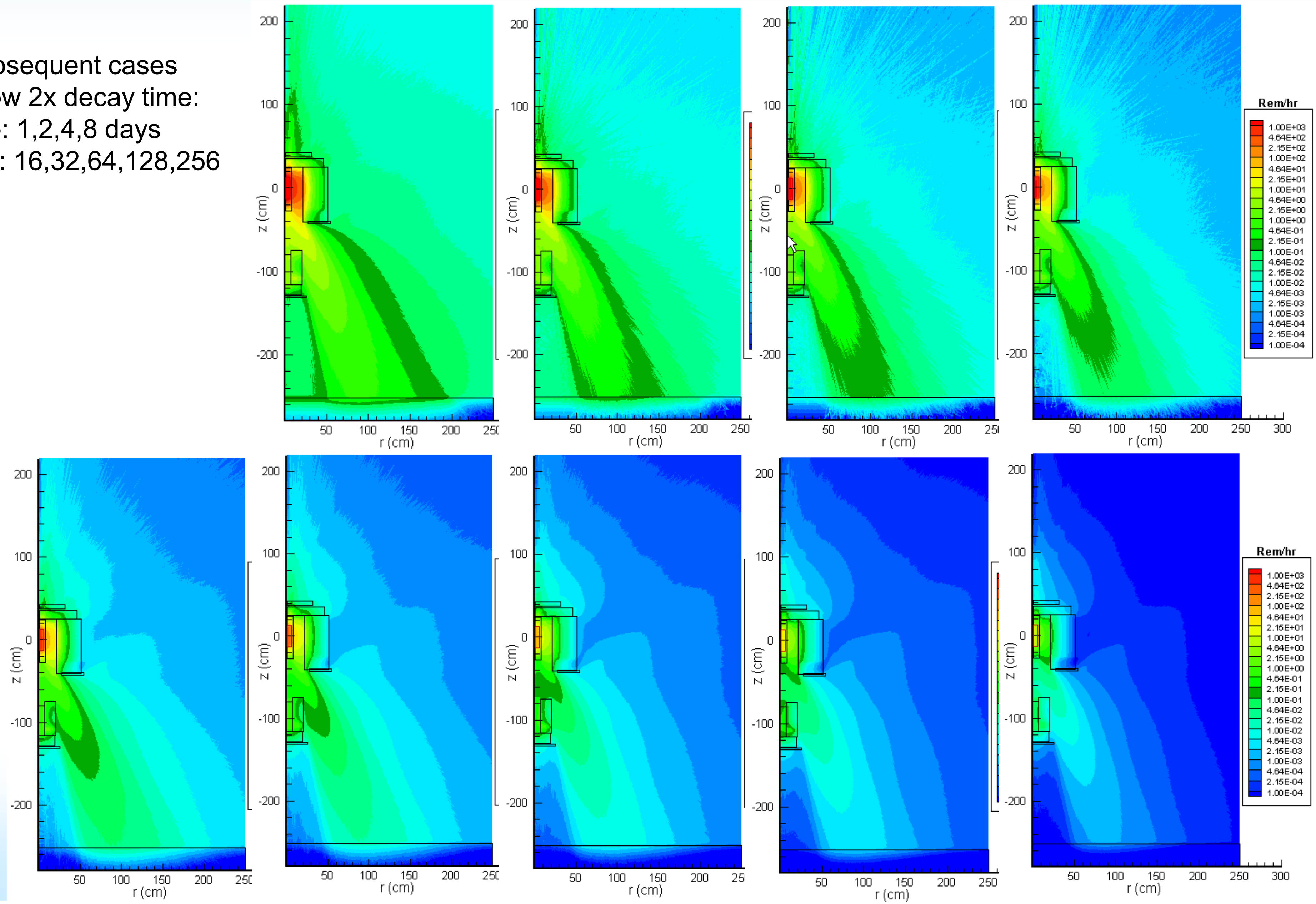


Final Run: 16 day decay stowed



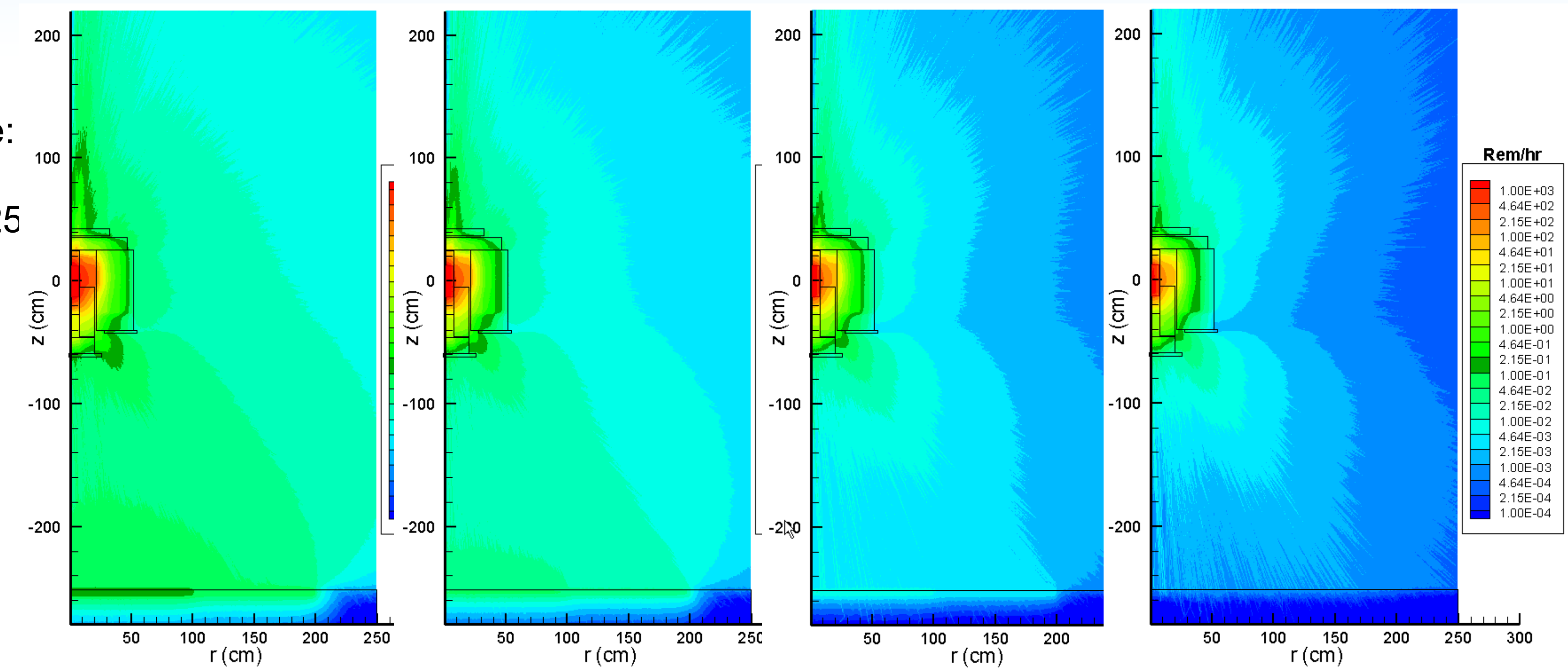
After Final Run, Platen Withdrawn

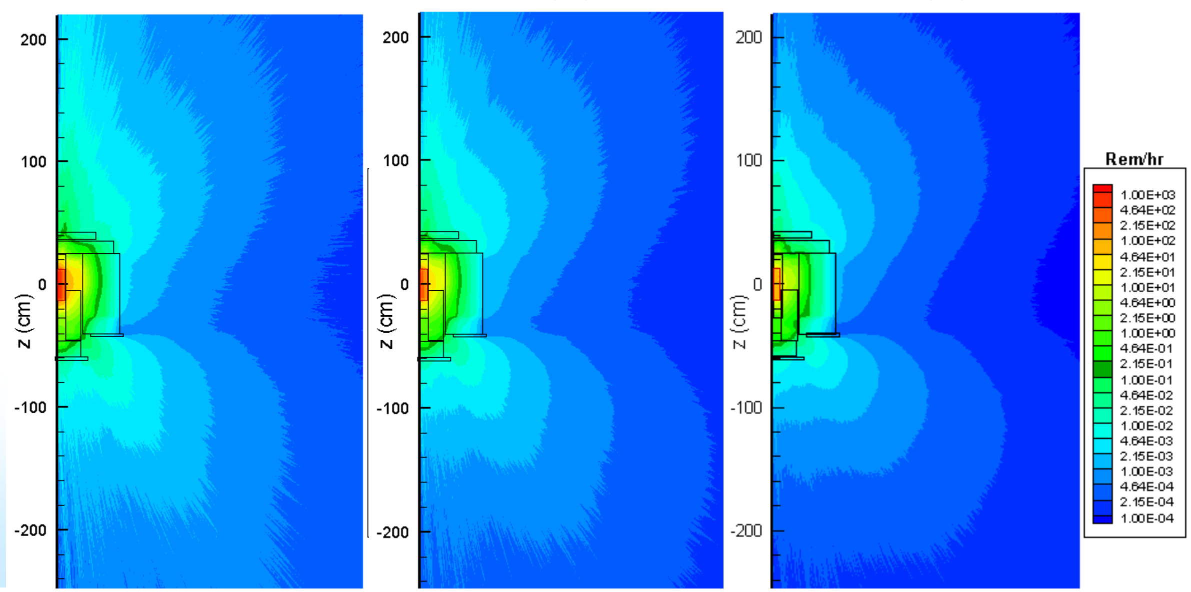
Subsequent cases
show 2x decay time:
Top: 1,2,4,8 days
Bot: 16,32,64,128,256



After Final Run, Platen Stowed

Subsequent cases
show 2x decay time:
Top: 1,2,4,8 days
Bot: 16,32,64,128,25

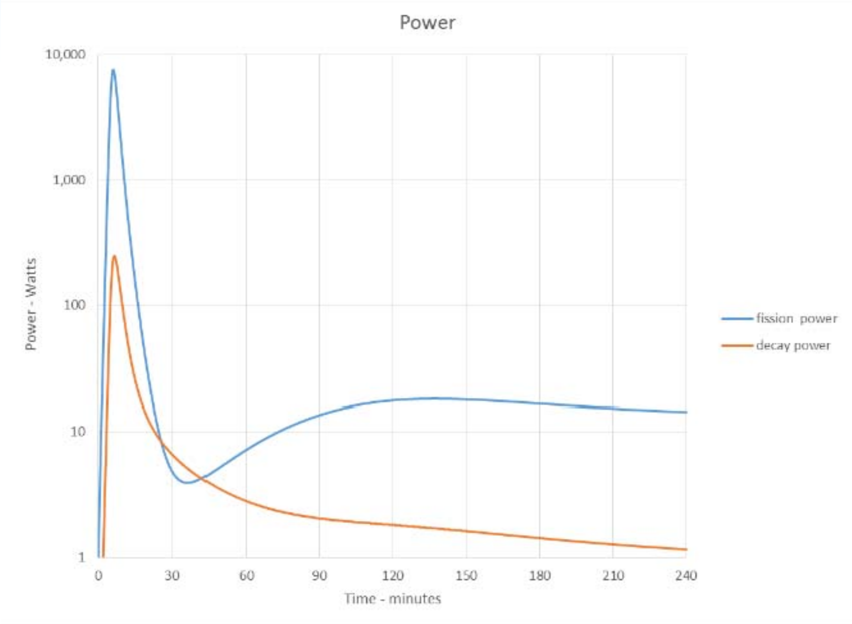


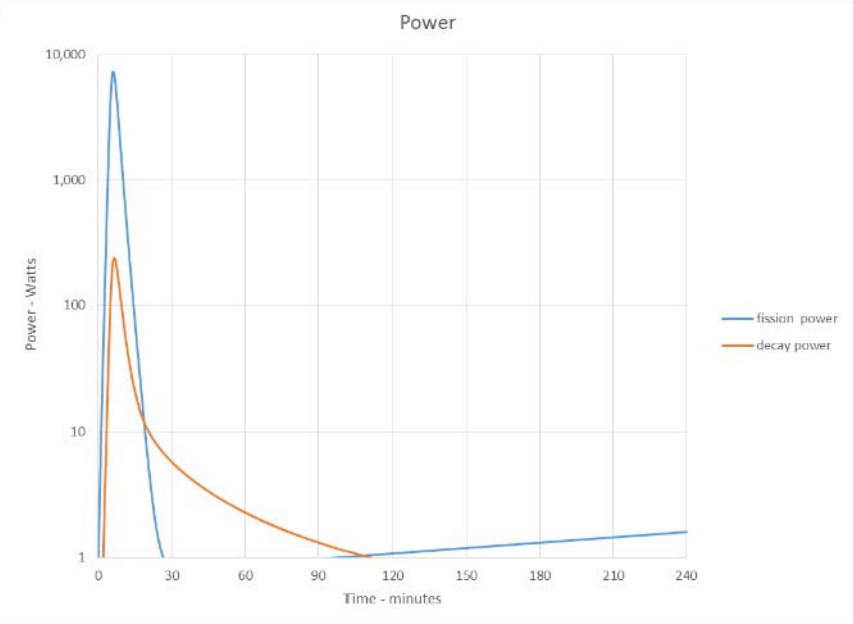


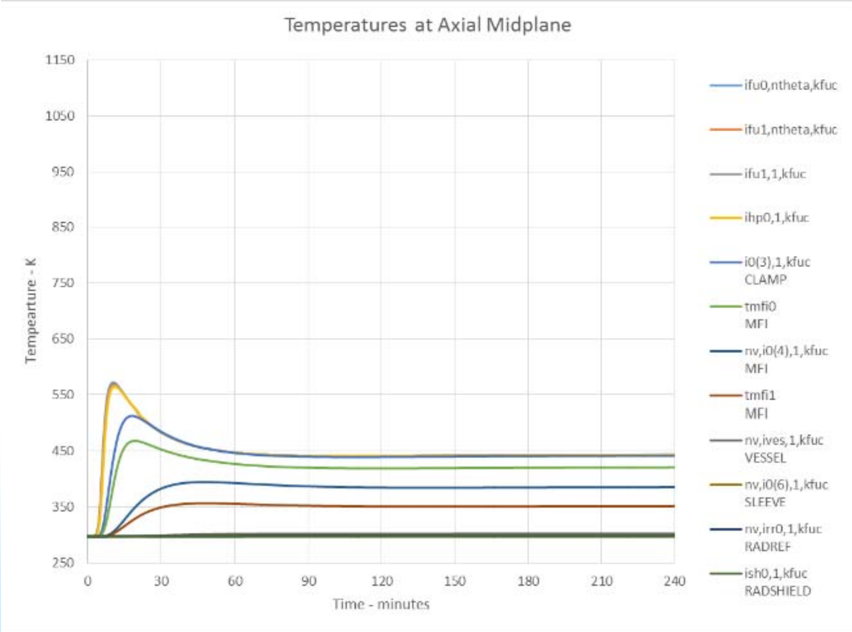
Modeling Sensitivities

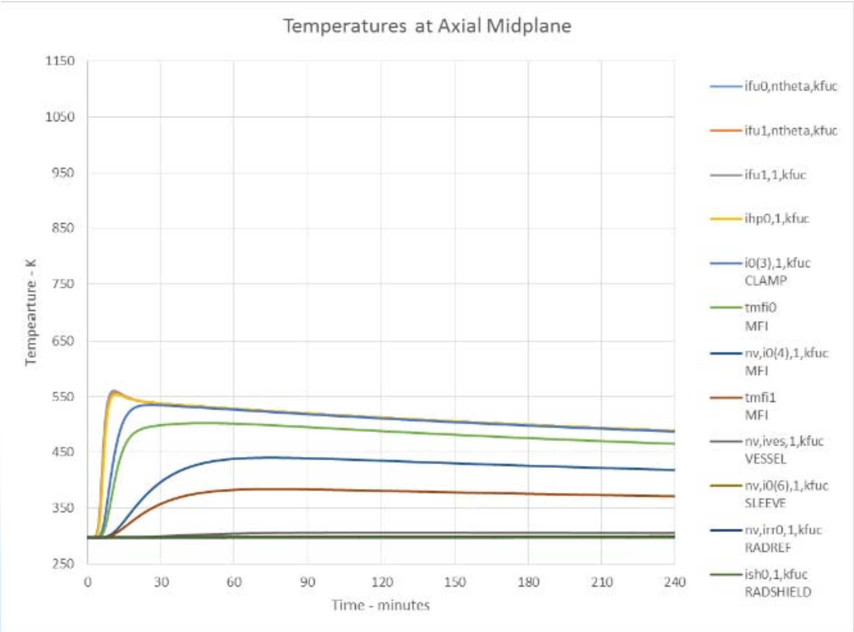
- Following charts looks at
  - Impact of insulation modeling
    - The mli thermal conductance is difficult to model, and more difficult to predict the effect of compression, which will likely occur in the axial mli between the fuel and axial reflector.
  - Impact of using the average fuel temperature for feedback, or a regional feedback approach which applies higher feedback coefficient to higher-worth regions and vice-versa.
    - The regional approach is used for all analyses presented, which should be more accurate.
  - Impact of neutron generation time
    - Neutron generation time can be important for prompt insertions, albeit very high >several dollars insertions. It is not expected to impact KRUSTY results (even in the worst possible case), but calculations were performed to confirm this.

Older Case: KRUSTY 20 cent insertion poorly-insulated core (left), well-insulated (right)



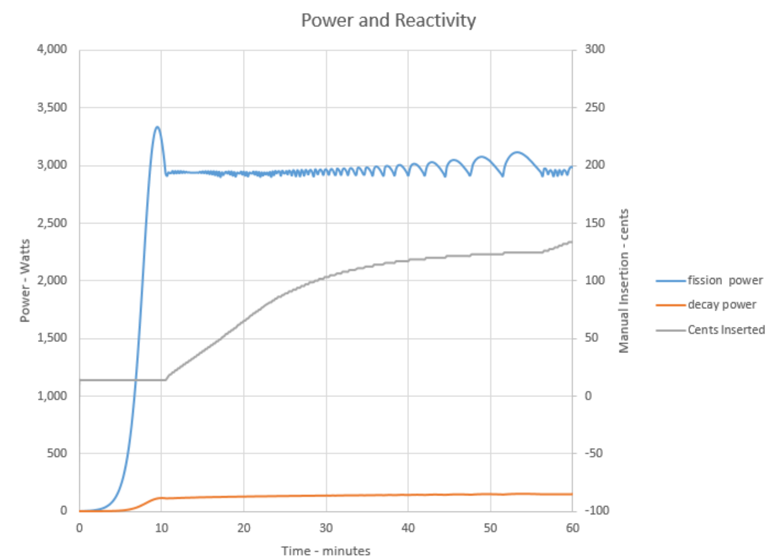


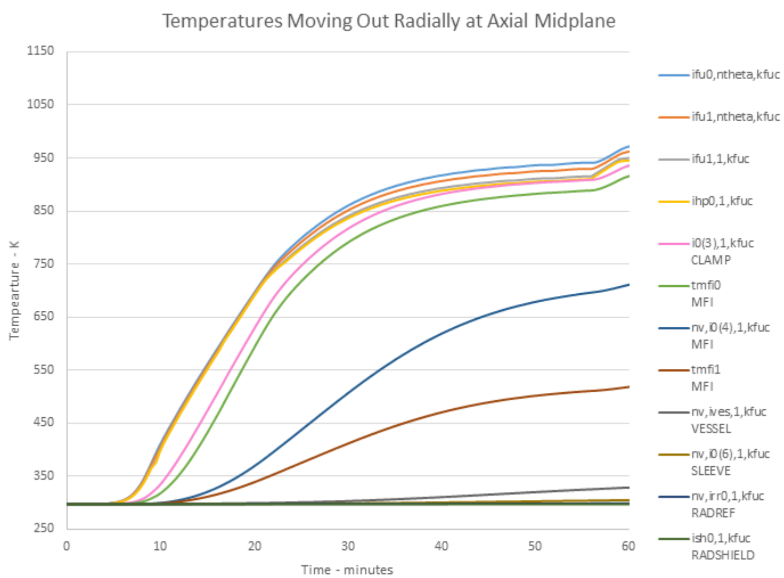




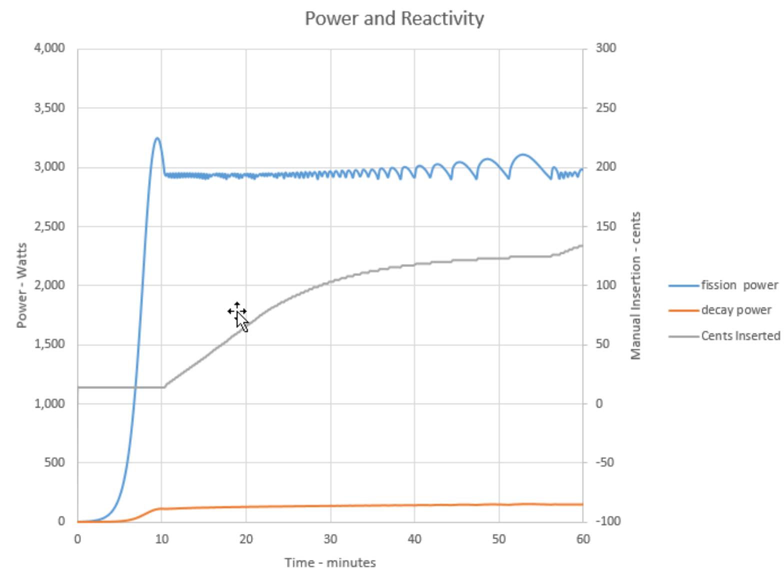
Effect of regional feedback – Final Run

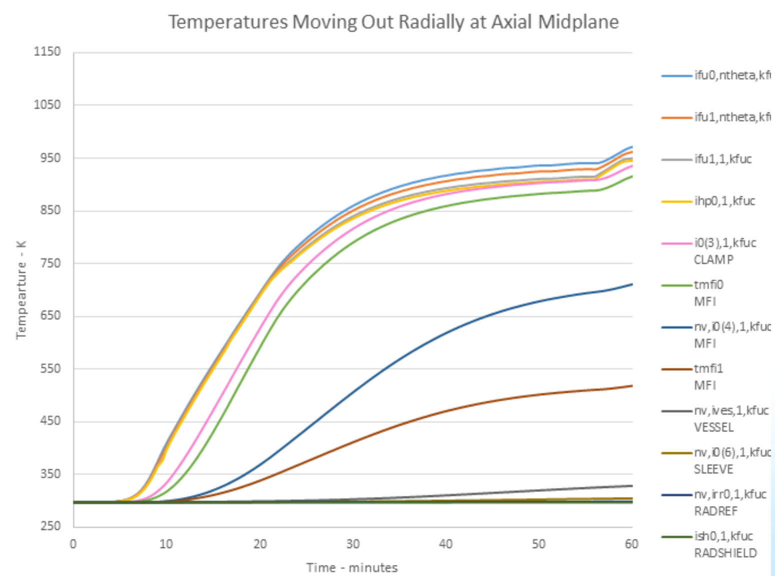
Feedback on Ave Fuel Temp





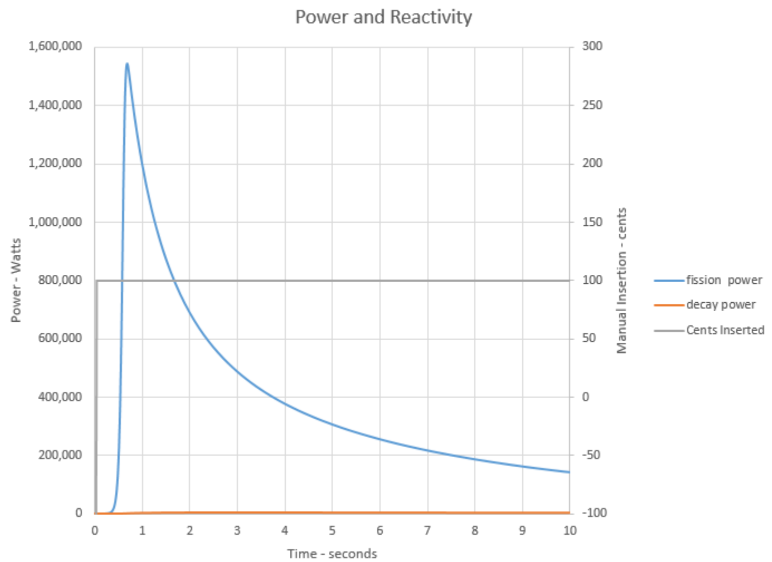
Feedback on Regional Weighted Fuel Temp

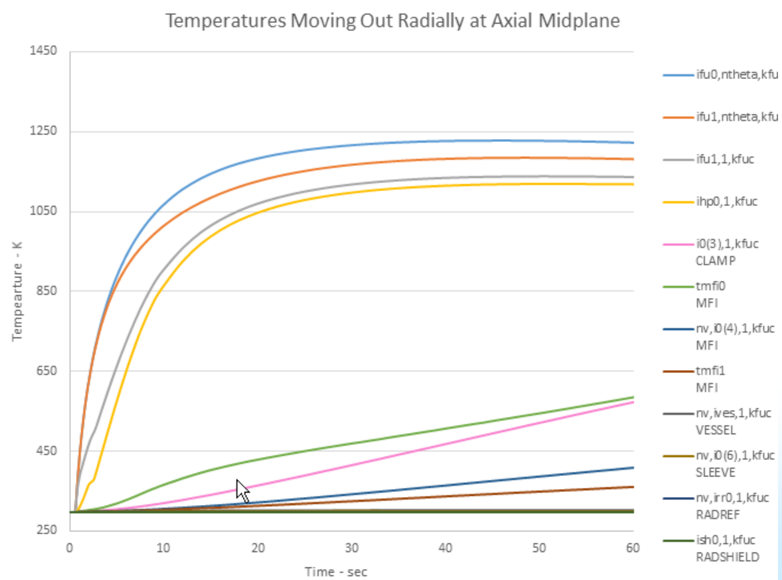




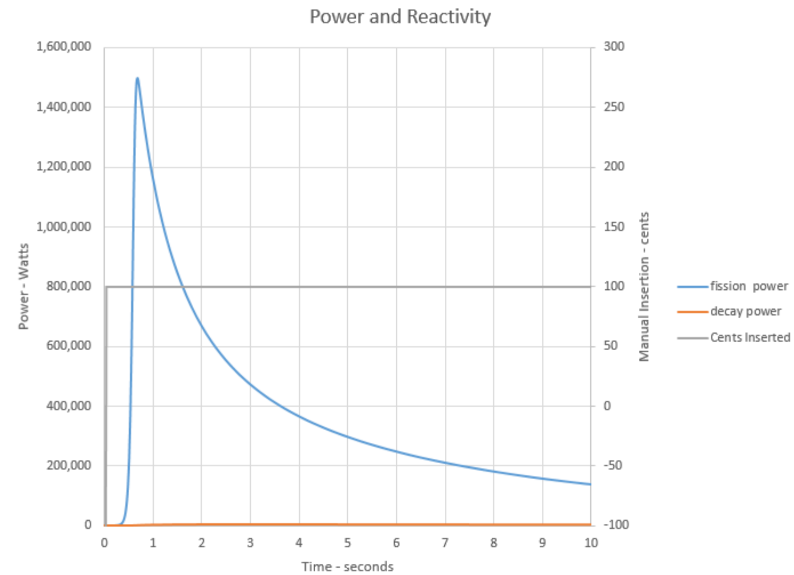
Effect of regional feedback - $1 Step

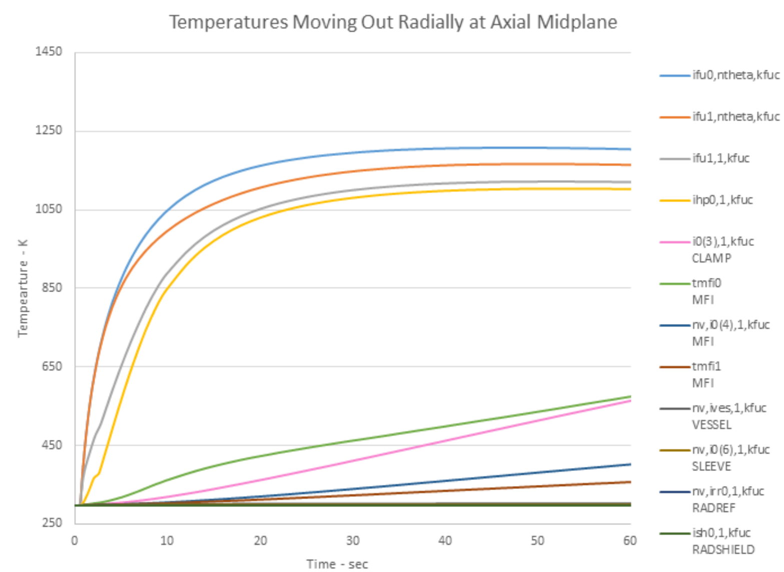
Feedback on Ave Fuel Temp





Feedback on Regional Weighted Fuel Temp





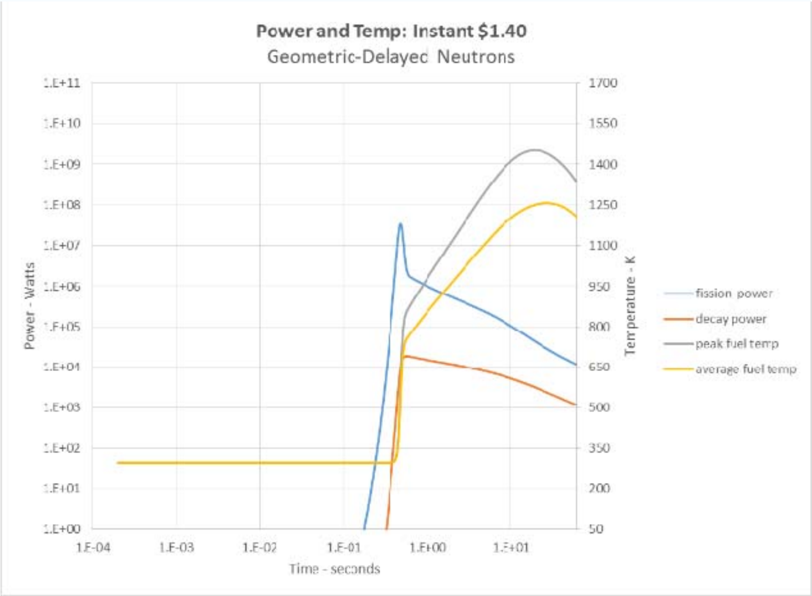
Impact of Neutron Generation Time

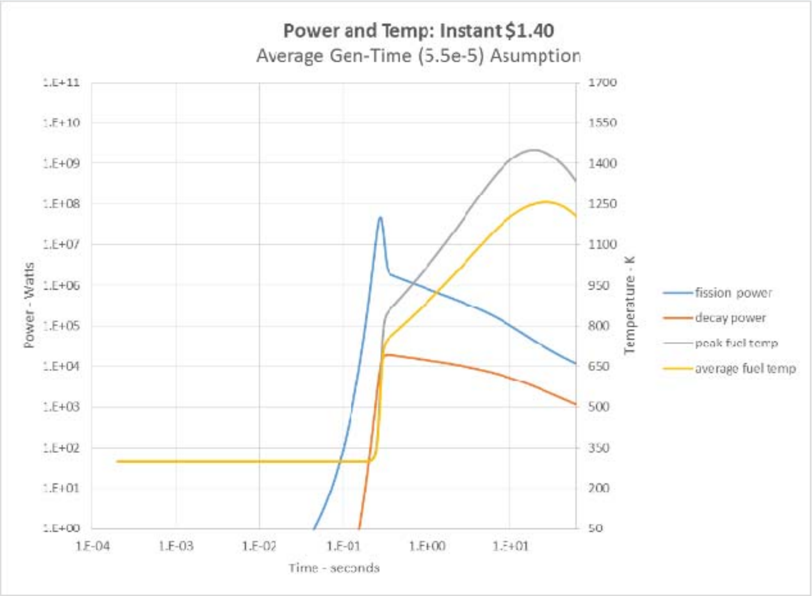
- Performed analyses at $1, $1.1, $1.2, $1.4, $1.8, $2.6
  - KRUSTY geometric delayed groups
  - Fast generation time (fuel and nearby reflector) = 5.5e-8
  - Average generation time of system = 3.5e-5
  - Geometric group, but heat pipes do not kick on.

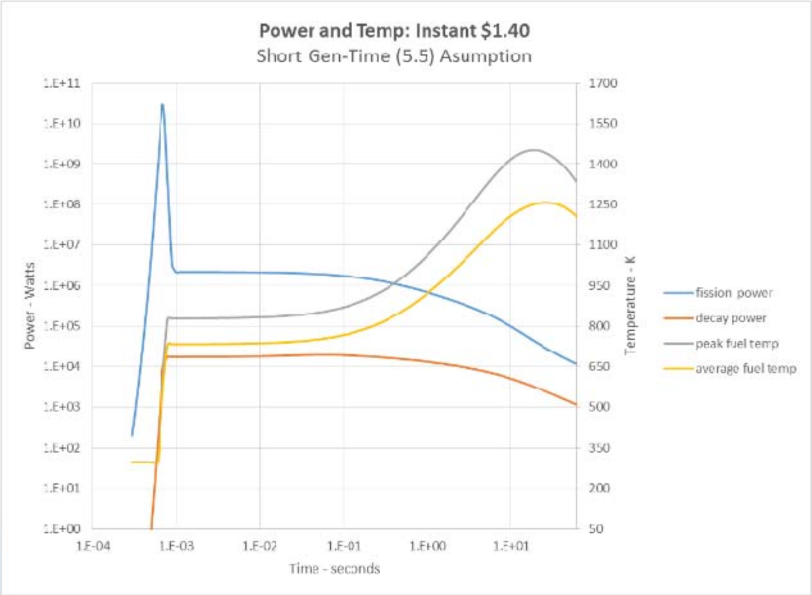
Geometric-delayed groups (note - old KRUSTY design with $3.5 excess

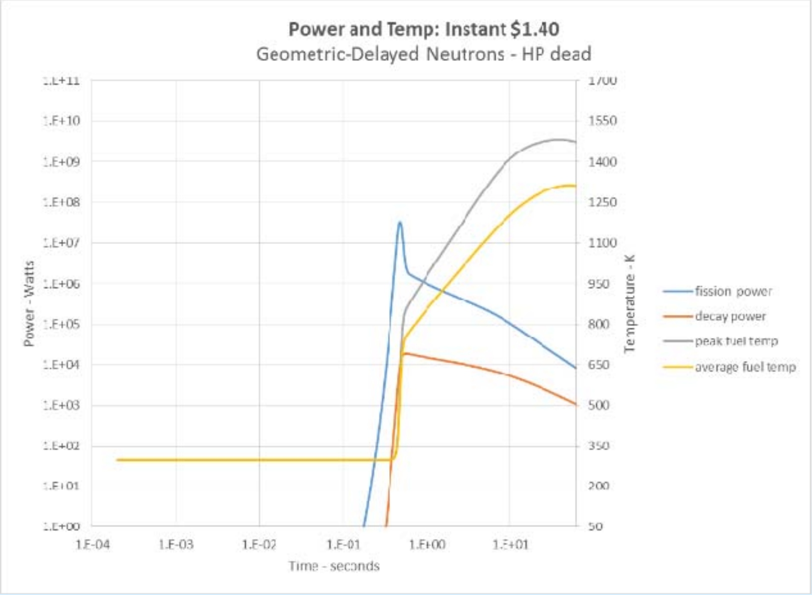
		keff	lifetime	delta-K	group life	fractional worth	time constant
krst7q0	baseline	1.02486	3.45E-05	0.00125	2.68E-03	0.00122	2.58E+02
krst7q1	cut all but 5 cm of shield	1.02361	3.13E-05	0.00199	3.50E-04	0.00194	1.98E+03
krst7q2	cut all but 2 cm of shield	1.02162	3.07E-05	0.00409	1.71E-03	0.00399	4.04E+02
krst7q3	cut all shielding	1.01753	2.39E-05	0.00230	9.98E-04	0.00224	6.94E+02
krst7q4	cut 5% of ref	1.01523	2.17E-05	0.00742	7.20E-04	0.00724	9.62E+02
krst7q5	cut 10% of ref	1.00781	1.66E-05	0.00825	5.42E-04	0.00805	1.28E+03
krst7q6	cut 15% of ref	0.99956	1.22E-05	0.00936	3.83E-04	0.00913	1.81E+03
krst7q7	cut 20% of ref	0.99020	8.73E-06	0.08555	9.62E-05	0.08347	7.20E+03
krst7q8	cut 50% of ref	0.90465	4.48E-07	0.13492	2.70E-06	0.13165	2.57E+05
krst7q9	cut 75% of ref (rad more)	0.76973	5.46E-08	0.14260	1.84E-07	0.13914	3.77E+06
krst7q10	cut all of rad ref + axref	0.62713	2.52E-08				

Impact of Neutron Generation Time (case krst1f)



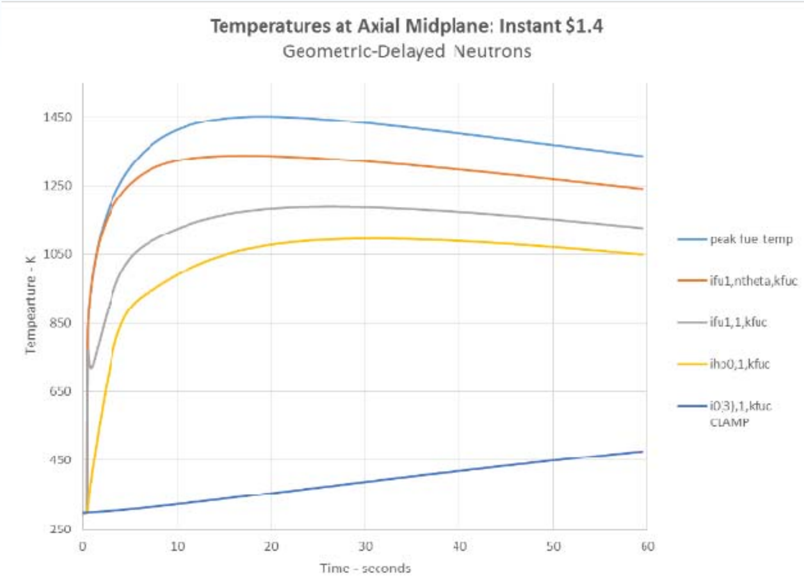


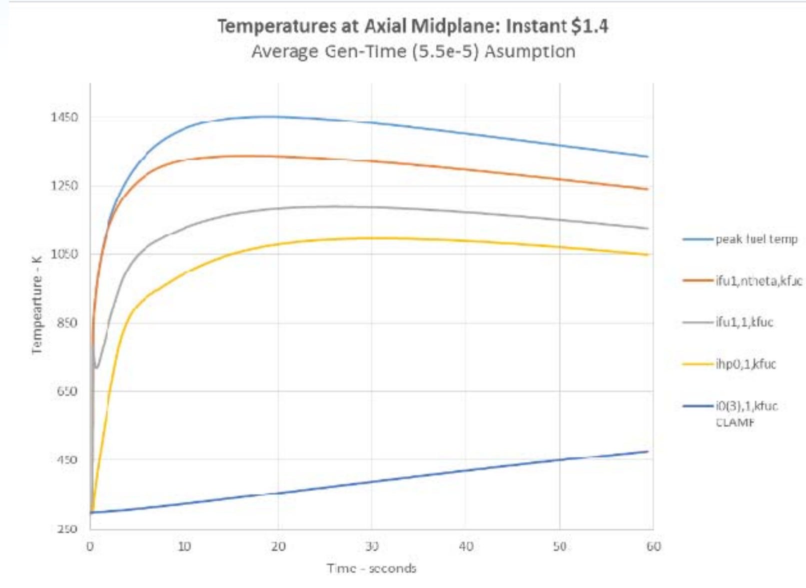


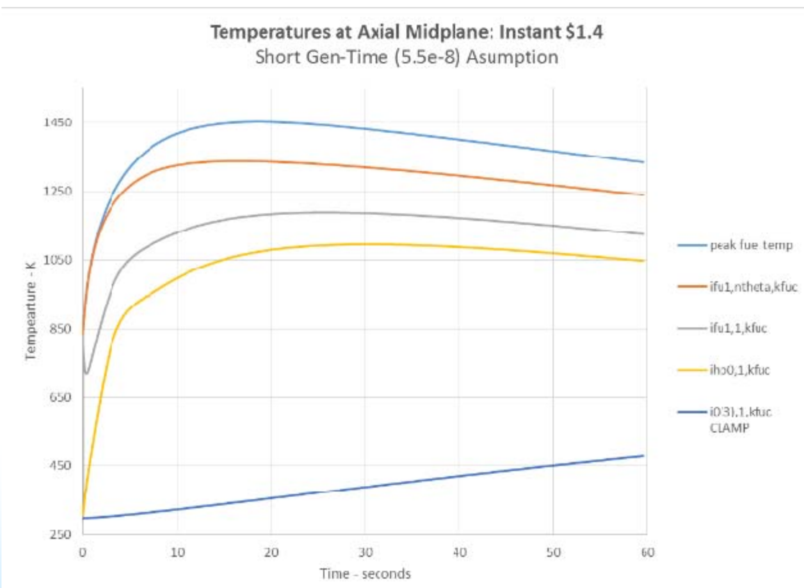


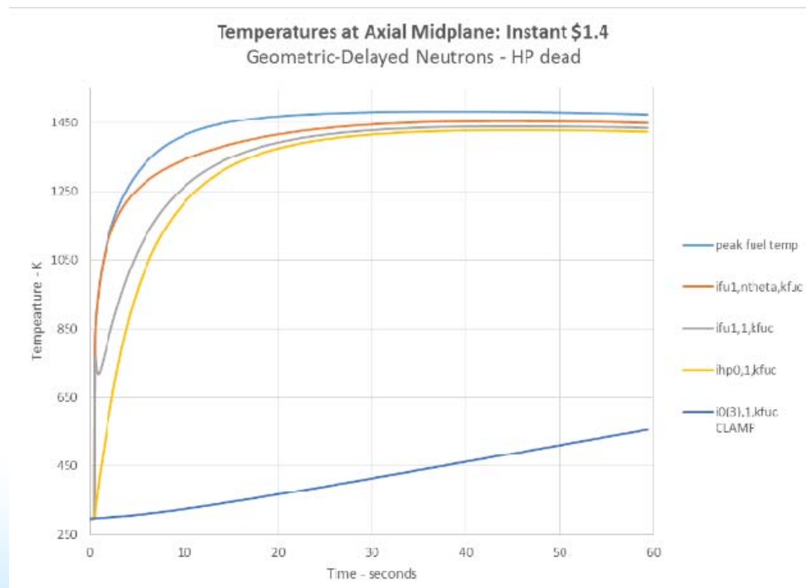
Significant difference in power spike, but no difference in temperatures

Impact of Neutron Generation Time (case krst1f)







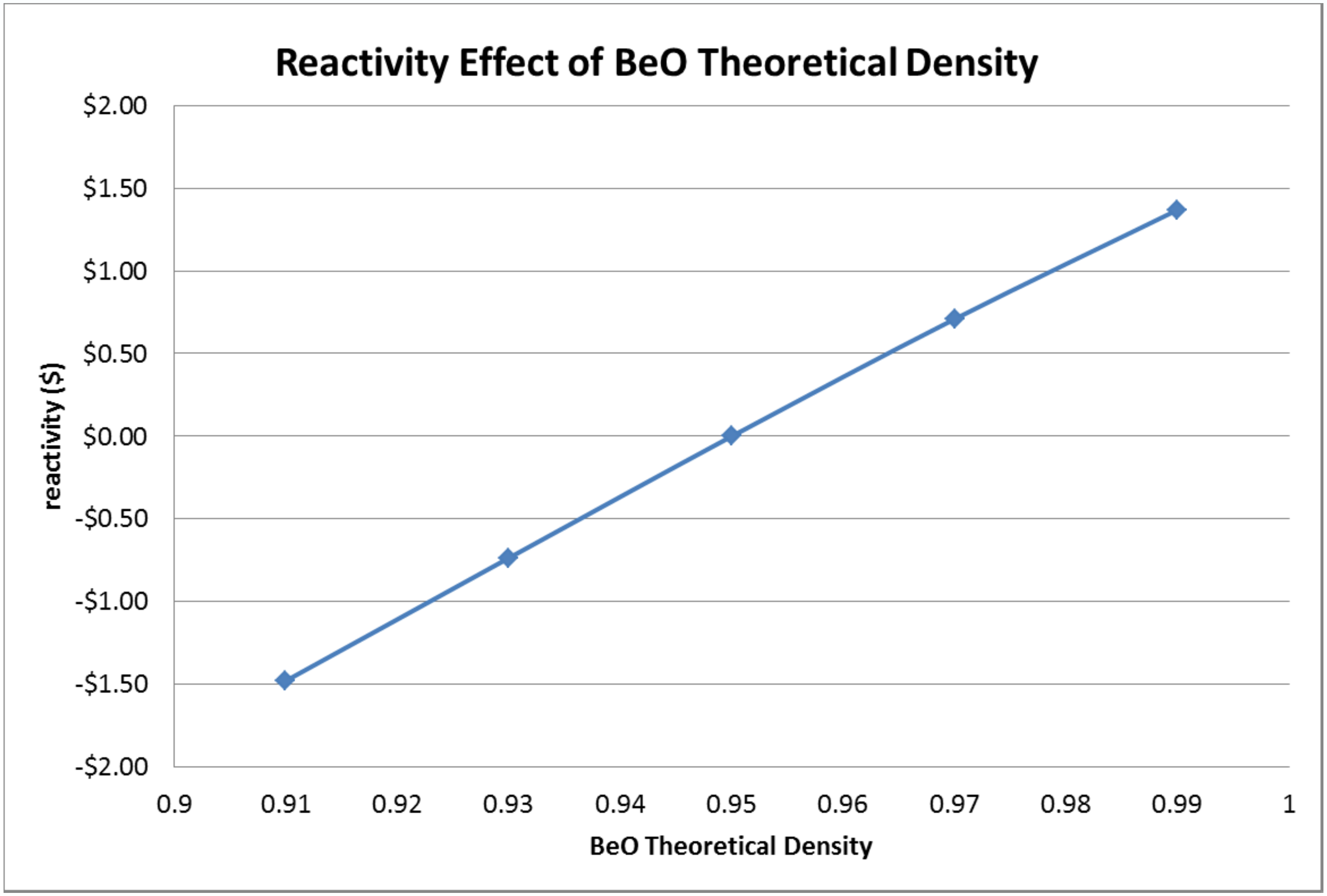


No difference with generation time, lower-right shows effect of heat pipes.

Impact of Neutron Generation Time

- Generation time has no net result on transients.
  - Even in the $2.6 case the end result was the same.
- The impact on peak temperature due to theheat pipes not "turning on" also was small.
  - It might reduce the survivable prompt transient by 1 or 2 cents.
    - Survivable meaning no partial fuel melt.
- None of the possible transients evaluated would result in destructive yield, worst case a potential mess in the vessel.
  - Fuel redistribution will initially decrease reactivity because melting will first occur by definition at highest worth region, and it's transfer will result in decrease in reactivity.
    - A full melting of fuel and a pooling/recasting into a shorter cylinder without a central hole could increase reactivity.
      - But gaps for flow below core could be designed to prevent this (assuming the existing gaps do not do the trick), or a Moly cylinder in safety rod region.
  - This discussion academic regardless, fuel melt scenarios cannot happen with proper insertion controls/procedure.

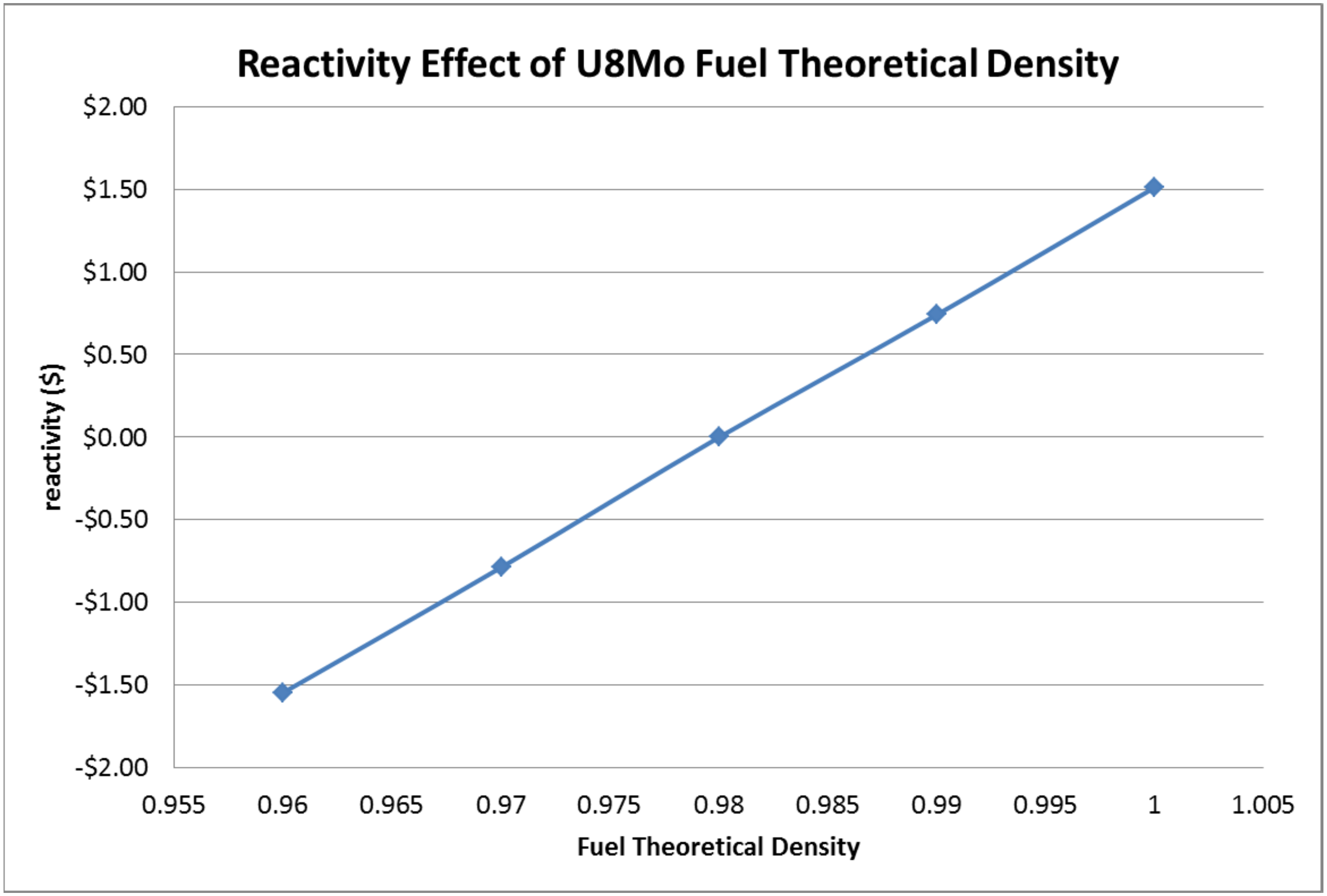
Design Sensitivity -- BeO Density



Every percent in BeO T.D. is worth about 35 cents.

This is an older design, but effect should be similar

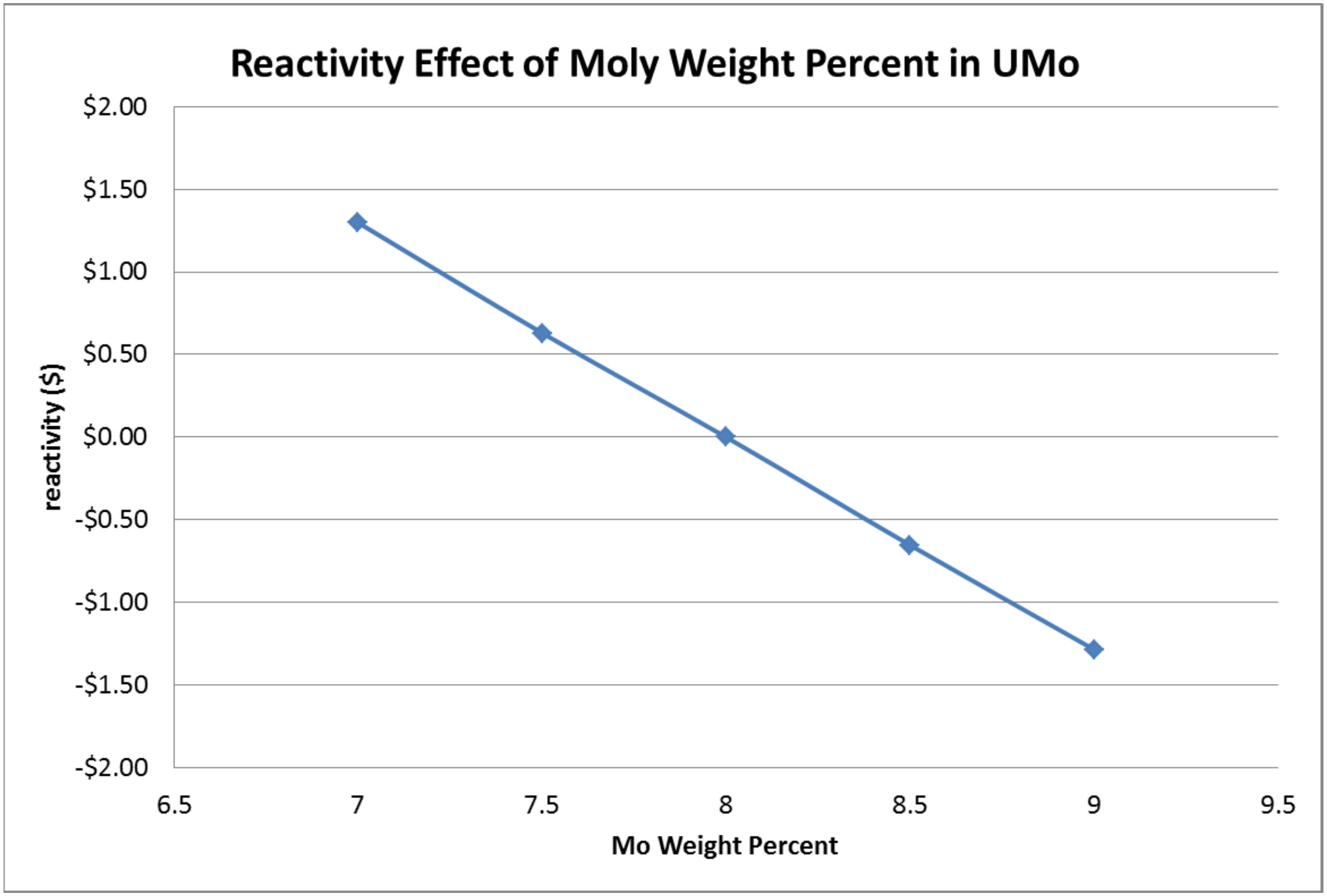
Design Sensitivity -- Fuel Density



Every percent in fuel T.D. is worth about 75 cents.

This is an older design, but effect should be similar

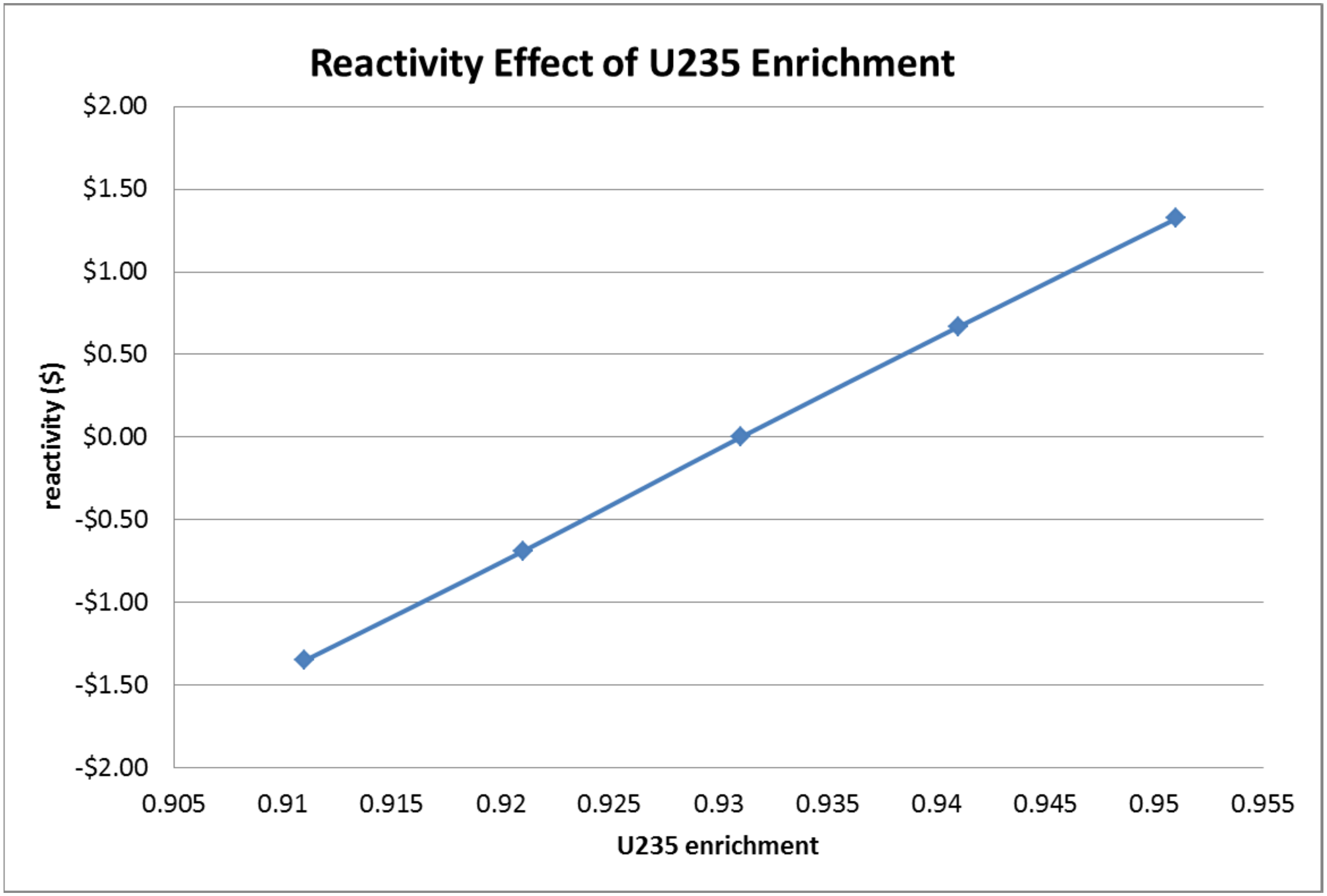
Design Sensitivity -- Fuel Moly Weight Percent



Every weight percent in Mo is worth about $1.3

This is an older design, but effect should be similar

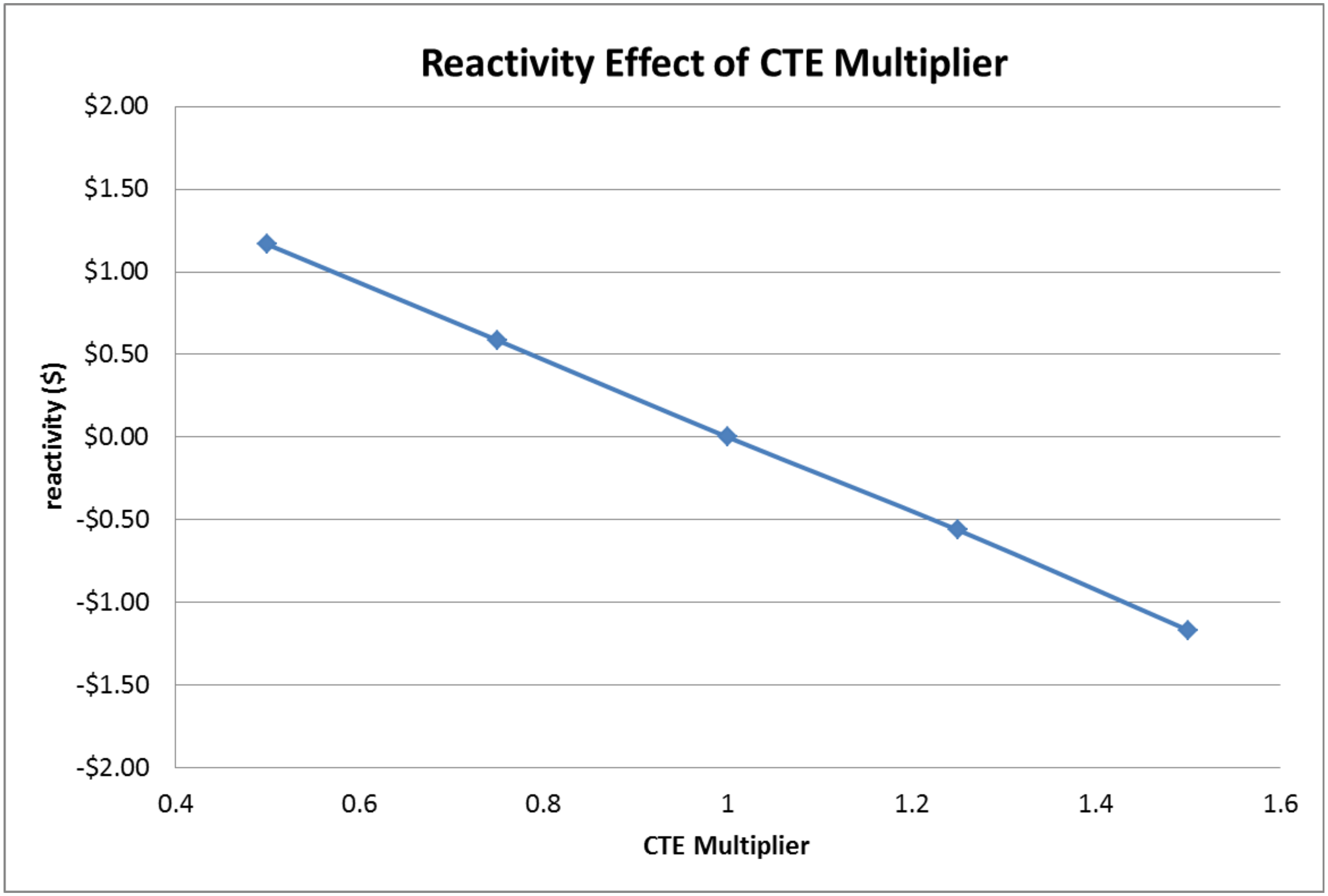
Design Sensitivity -- U235 Enrichment



Every percent in enrichment is worth about 65 cents.

This is an older design, but effect should be similar

Design Sensitivity -- Changes in Fuel CTE



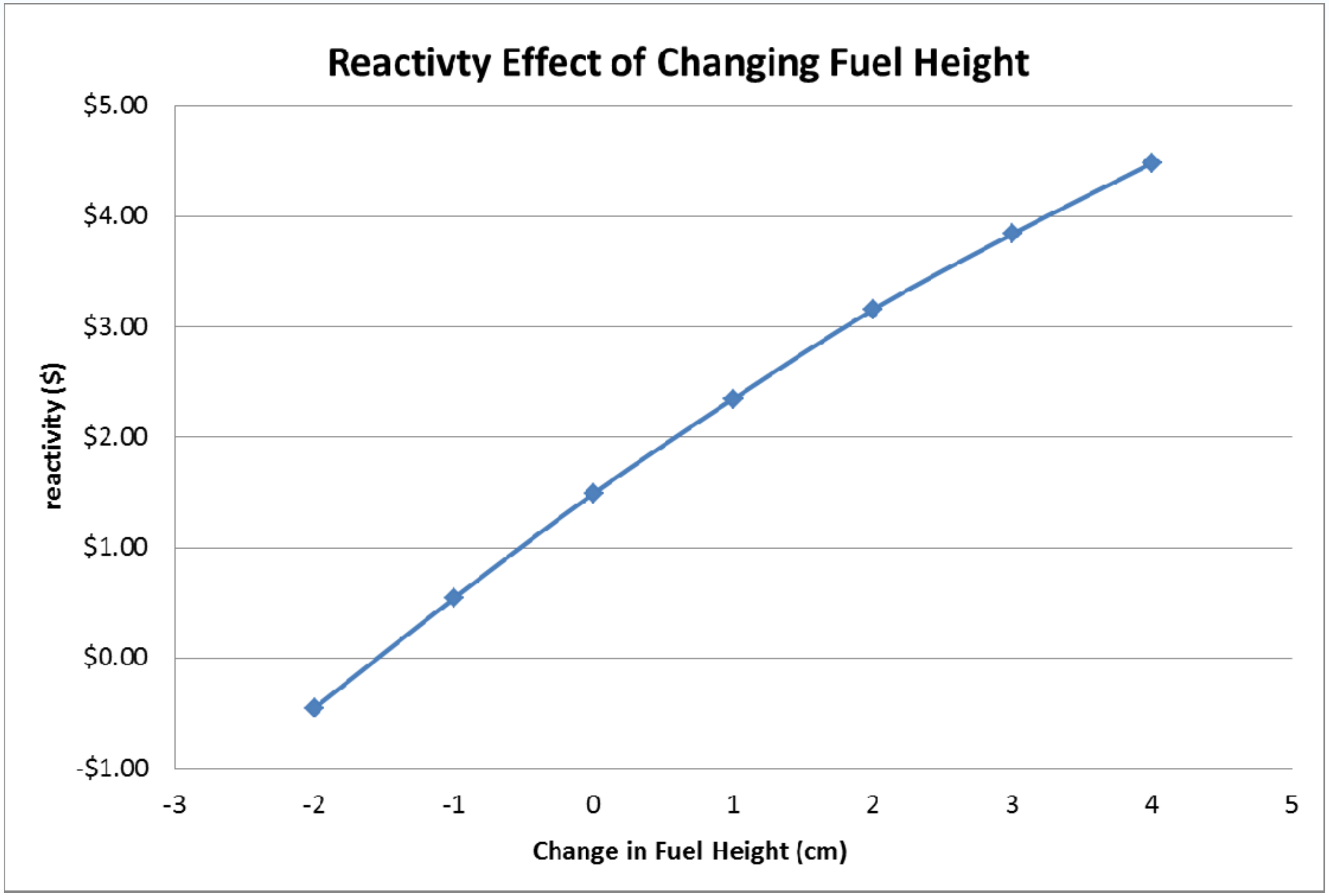
MRPLOW CTEs (1x)

300	11.5
350	12.1
400	12.8
450	13.4
500	14.0
550	14.6
600	15.2
650	15.8
700	16.4
750	17.0
800	17.6
850	18.2
900	18.8
950	19.4
1000	20.0
1050	20.6
1100	21.2
1150	21.8
1200	22.4

If CTE is 25% higher than current model it will drop warm reactivity by $.60, or vice versa.

This is an older design, but effect should be similar

Design Sensitivity -- Core Length

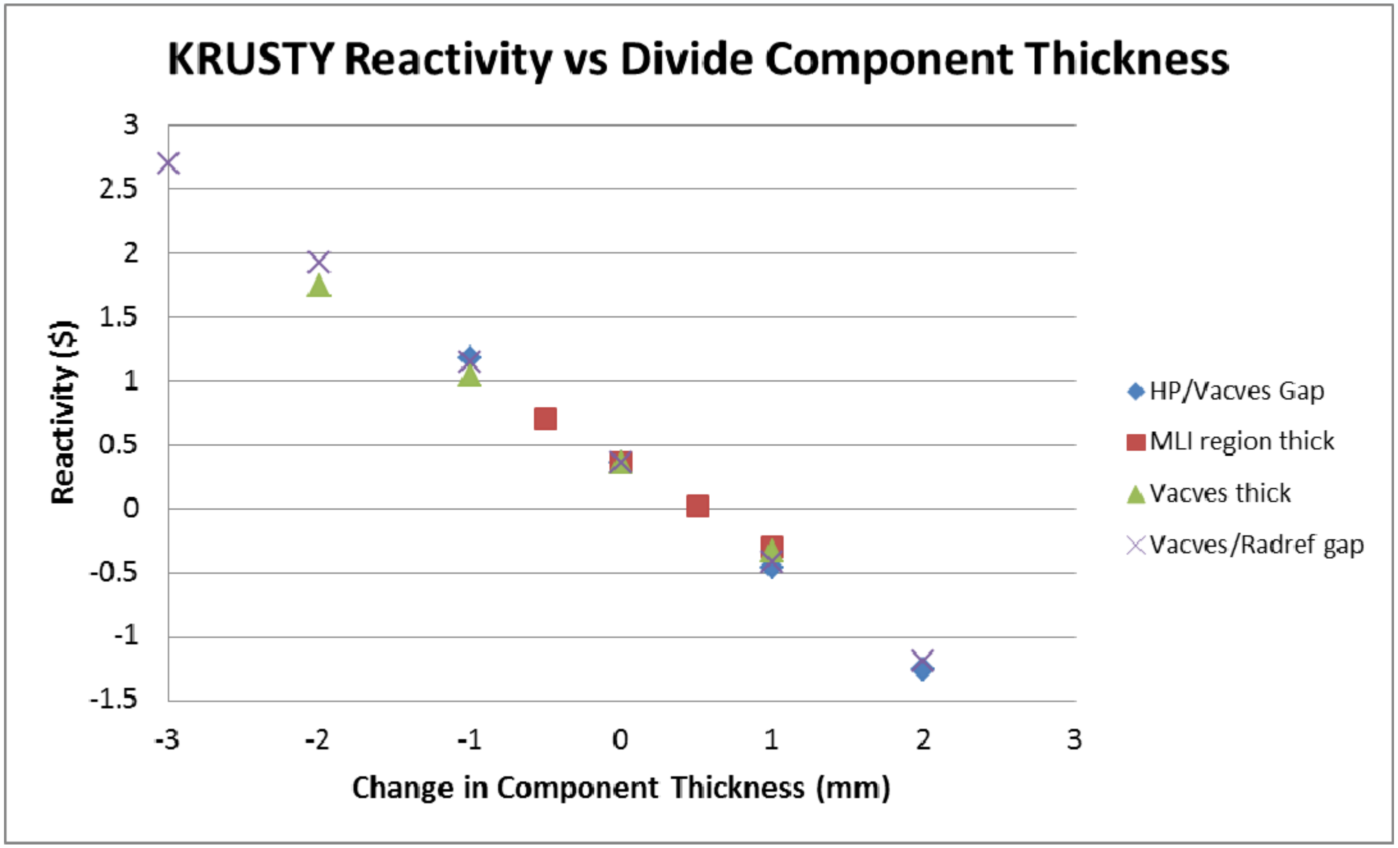


The is for the fully inserted, full BEO-stack condition; thus the nominal case is our current $1.50 margin. The first cm adds about $0.85, with diminishing returns

This calculation keeps the overall reactor dimensions the same, but replaces BeO axial reflector with fuel (so instead of 25 cm fuel with 10 cm axref each side you might have 27 cm of fuel with 9cm of axref on each side – all other dimensions remain the same)

This is an older design, but effect should be similar

Possible Future Reactivity Change: Size of the Divide



Reactivity is very sensitive to every millimeter of the Divide, about 75 cents per mm. What's interesting is that it makes almost no difference is there is mass in the Divide or void. In general the increased reflection balances our any increase absorption.

Note: This is for an older design, and will be different (likely smaller) with the current highly reflected design).

KRUSTY (krst1f) Sensitivity to Cross Section Set

Cold (room temperature), Short stack = -2.47 cm, Table height = -2.8 cm

Cross Section Set	K-eff	error	details
space07 (endf70)	1.00023	0.00007	space07, based on endf70
mcnp endf70	1.00029	0.00002	xsdir from opt/data/endf70, dated 9/4/2015
mcnp endf71	1.00156	0.00002	xsdir.2015.01.29 from opt/data/endf71/end71_all/xdata

<u>endf71 increases keff by 0.00132 +/- .00003</u>

From here on out, reactivity change values in cents, where beta-eff = .0069

<u>endf71 increases keff by 18.4¢ +/- 0.04¢</u>

space07 is a homegrown mcnp library built by NEN-5 based on endf70 data (for the purpose of having cross sections at numerous temperatres (in some cases every 10 degrees) .

All cases above use beo.60t s(α,β)

Step-by-step change from endf71 to end70

krst1h71	endf71 (then step to 70 below)	1.00156	0.00002
krst1h74	Be	0.99950	0.00002
krst1h75	U235	0.99946	0.00003
krst1h76	balance of fuel	0.99949	0.00003
krst1h77	balance of BeO	0.99956	0.00002
krst1h78	Fe56	0.99955	0.00003
krst1h79	W in Haynes 230	0.99962	0.00002
krst1h93	Ni58	0.99913	0.00002
krst1h80	Ni60	0.99907	0.00002
krst1h81	Na23	0.99907	0.00002
krst1h82	Mo	0.99900	0.00002
krst1h83	B	0.99902	0.00003
krst1h84	C	0.99898	0.00003
krst1h86	rest of Fe (other than 56)	0.99901	0.00002
krst1h87	rest of Ni (other than 58, 60)	0.99905	0.00002
krst1h90	Cr52	1.00018	0.00002
krst1h91	Cr53	1.00003	0.00002
krst1h92	Cr50	1.00000	0.00002
krst1h88	rest of Cr	1.00004	0.00002
krst1h89	Mn	1.00026	0.00002
krst1h85	everything else to70	1.00029	0.00002

Sorted by highest worth on next slide

Change in going from endf70 to endf71

Be	29.9 ¢	± 0.4 ¢
Ni58	7.1 ¢	± 0.4 ¢
Cr53	2.2 ¢	± 0.4 ¢
Mo	1.0 ¢	± 0.4 ¢
Ni60	0.9 ¢	± 0.4 ¢
U235	0.6 ¢	± 0.5 ¢
C	0.6 ¢	± 0.6 ¢
Cr50	0.4 ¢	± 0.4 ¢
Fe56	0.1 ¢	± 0.5 ¢
Na23	0.0 ¢	± 0.4 ¢
B	-0.3 ¢	± 0.5 ¢
balance of fuel	-0.4 ¢	± 0.6 ¢
rest of Fe (other than 56)	-0.4 ¢	± 0.5 ¢
everything else to70	-0.4 ¢	± 0.4 ¢
rest of Ni (other than 58, 60)	-0.6 ¢	± 0.4 ¢
rest of Cr	-0.6 ¢	± 0.4 ¢
W in Haynes 230	-1.0 ¢	± 0.5 ¢
balance of BeO	-1.0 ¢	± 0.5 ¢
Mn	-3.2 ¢	± 0.4 ¢
Cr52	-16.4 ¢	± 0.4 ¢

Be9, Cr52, Ni58, and Mn55 differences examined in following cross section plots

Impact of s(α,β)

	k-eff	error	delta rho	error
endf71, beo.60t	1.00156	0.00002		
endf71, beo.01t	1.00171	0.00002	-2.2 ¢	± 0.4 ¢

The older s(α,β) (beo.01t) results in a k-eff ~2 cents then the current recommended beo.60t. So small difference between the two.

	k-eff	error	delta rho	error
endf71, beo.60t	1.00156	0.00002		
endf71, no s(α,β)	1.00026	0.00002	-18.8 ¢	± 0.4 ¢

The overall impact of using a s(α,β) scatter correction, versus none at all is ~19 cents (i.e. the use of s(α,β) increases k-eff by ~19 cents). Not very large, but not insignificant either.

Temperature Dependent ENDF7.0 vs 7.1

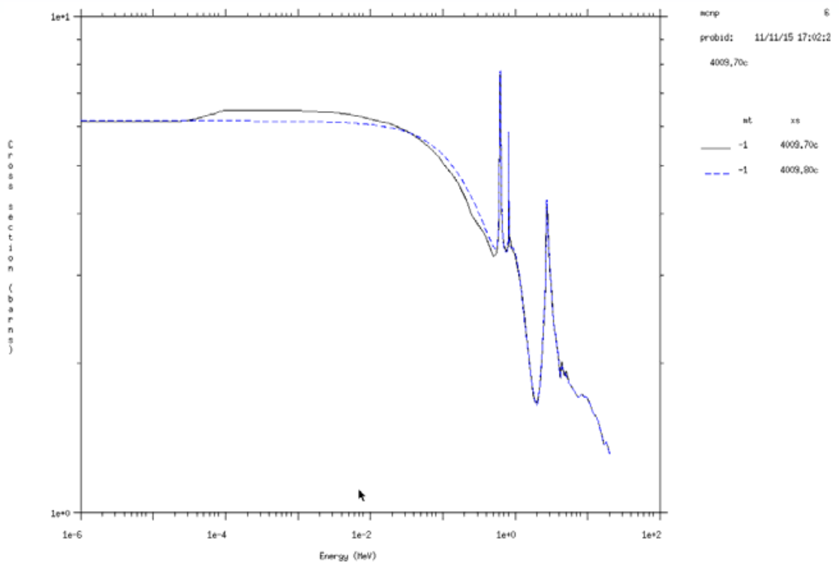
- The reason endf7.0 is used for the baseline calculations is because we have a large library at numerous temperature intervals, whereas standard endf7.1 is every 300 K.
- To check if there were any temperature dependent differences in the cross sections, several of the reactivity coefficients were calculated at 300 degree intervals with endf7.1 to compare wirh endf7.0
  – Error is ~0.4 cents in the difference.

Component	Temp(K)	Endf7.0	Endf7.1	Difference	Difference
All cold	295	1.01288	1.01411	0.00123	$ 0.176
Fuel	600	1.00958	1.01081	0.00123	$ 0.176
Fuel	900	1.00508	1.00625	0.00117	$ 0.167
Fuel	1200	0.99936	1.00057	0.00121	$ 0.173
Axref	600	1.01284	1.01409	0.00125	$ 0.179
Axref	1200	1.01273	1.01398	0.00125	$ 0.179
Radref	600	1.01297	1.01425	0.00128	$ 0.183
Radref	1200	1.01048	1.01173	0.00125	$ 0.179
Clamp	600	1.01274	1.01399	0.00125	$ 0.179
Clamp	1200	1.01259	1.01383	0.00124	$ 0.177
Average bias					$ 0.177

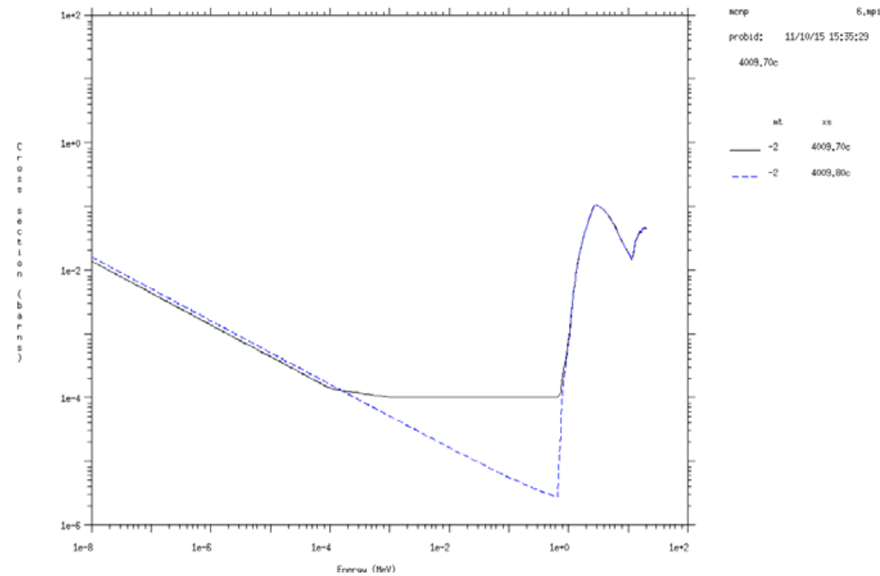
Results are very consistent at all temperatures of all key components, thus a bias of 17.7 cents can be (and has been for cases krst4a and beyond!) applied across the board to all KRUSTY results.

Be9: Difference ENDF7.0 and 7.1

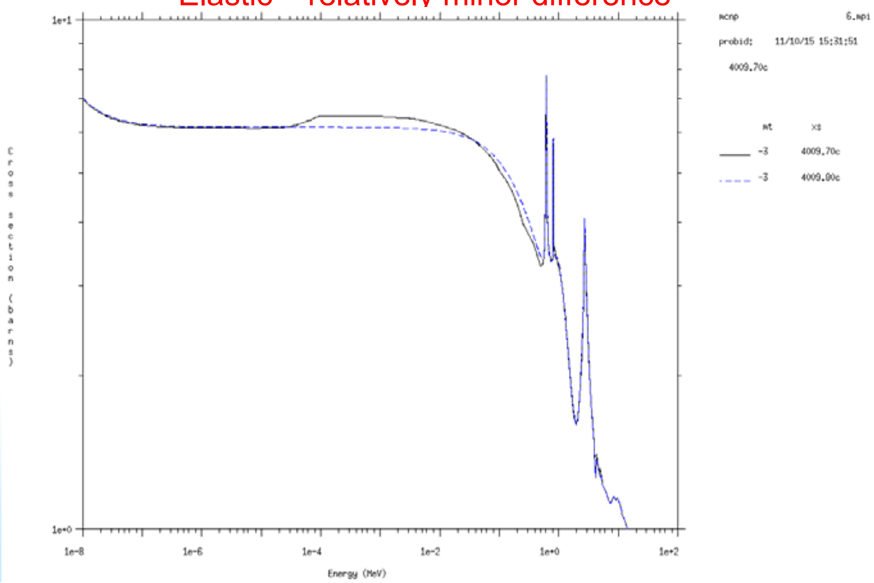
Total Cross Section Comparison



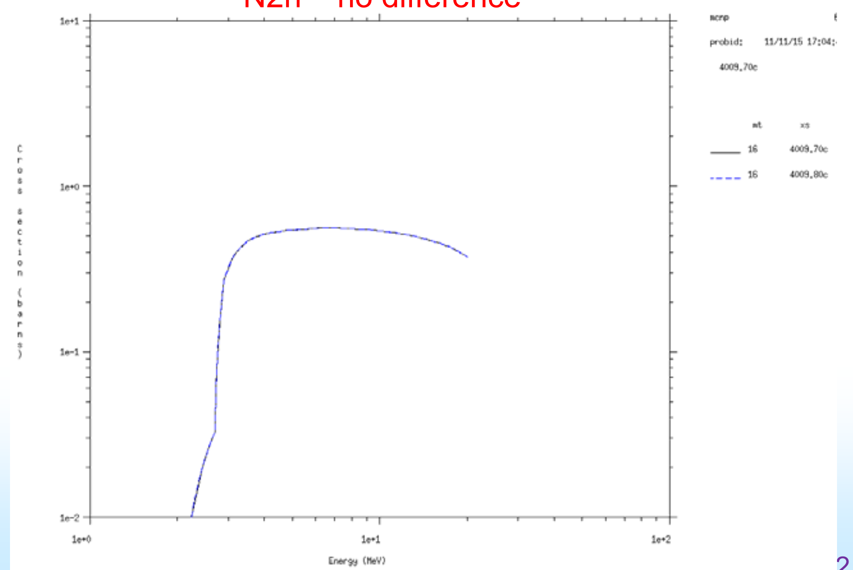
Absorption – 71 has much lower absorption, increasing keff



Elastic – relatively minor difference

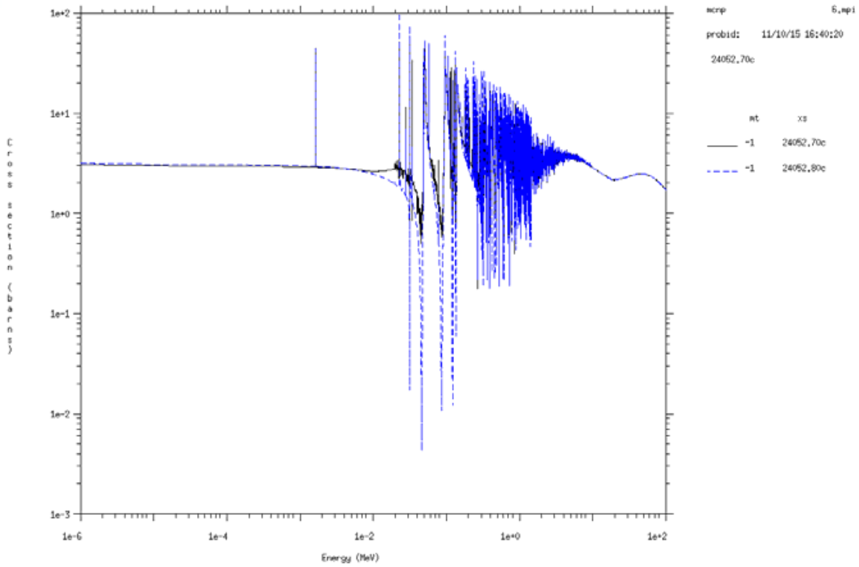


N2n – no difference

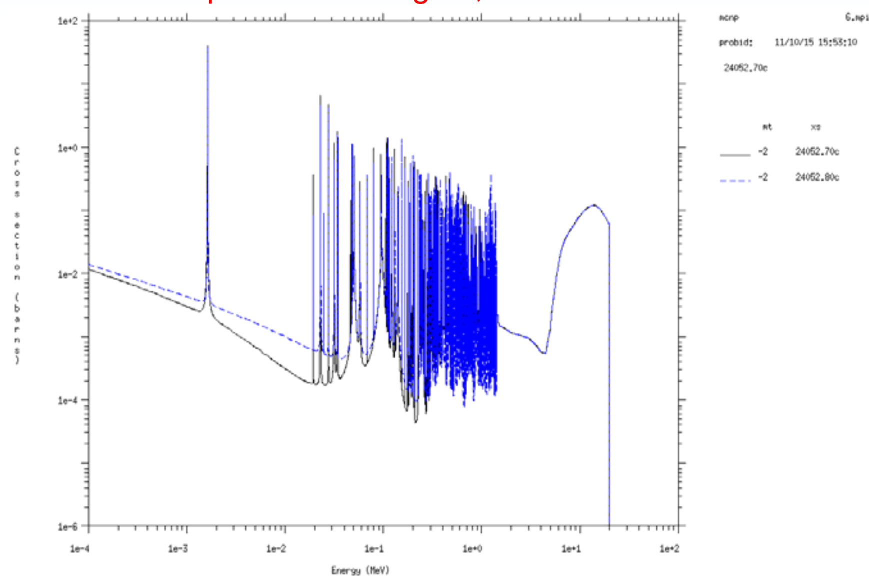


Cr52: Difference ENDF7.0 and 7.1

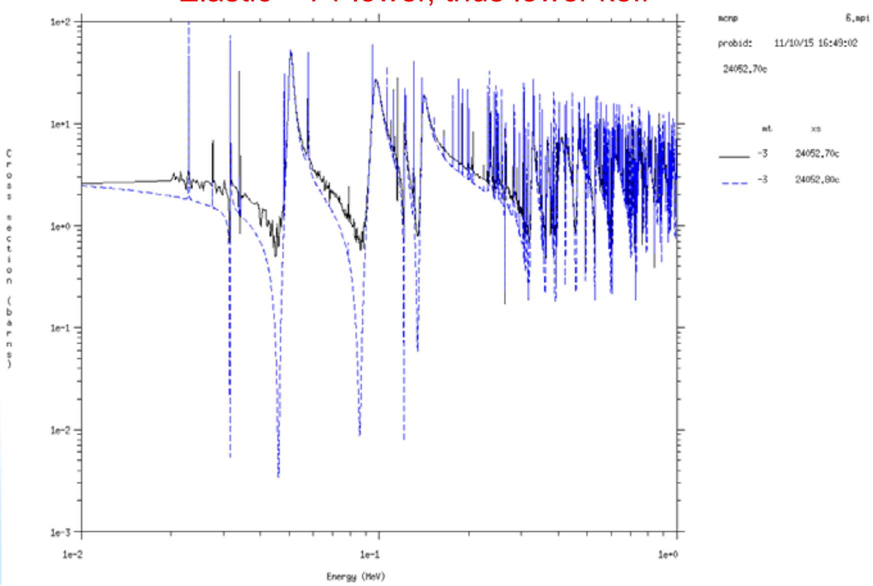
Total Cross Section Comparison



Absorption – 71 is higher, thus lower keff



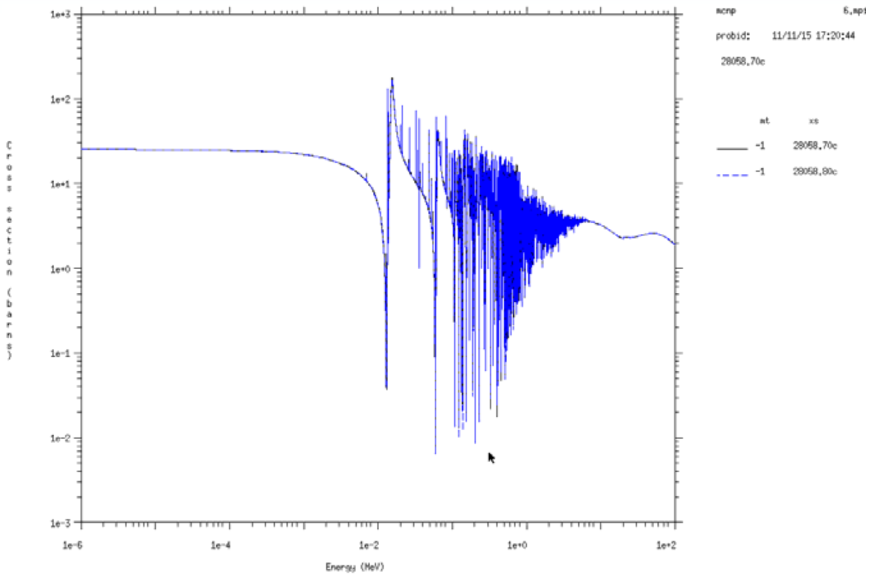
Elastic – 71 lower, thus lower keff



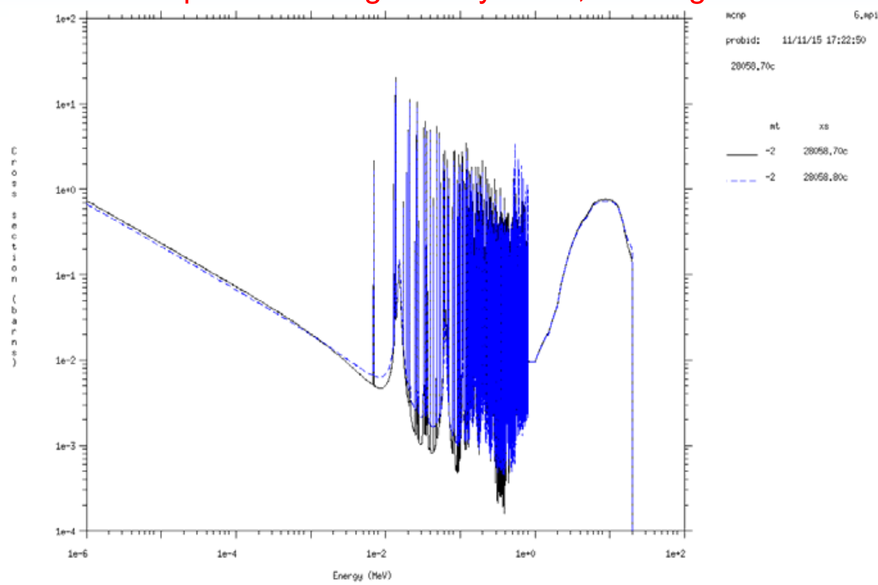
There is significant Cr in Haynes-230, in the HPs and bands between core and reflector (increased absorption hurts and increased scatter helps). Also, there is Cr in the vast SS-316 shield.

Ni58: Difference ENDF7.0 and 7.1

Total Cross Section Comparison



Absorption – 71 is generally lower, thus higher keff

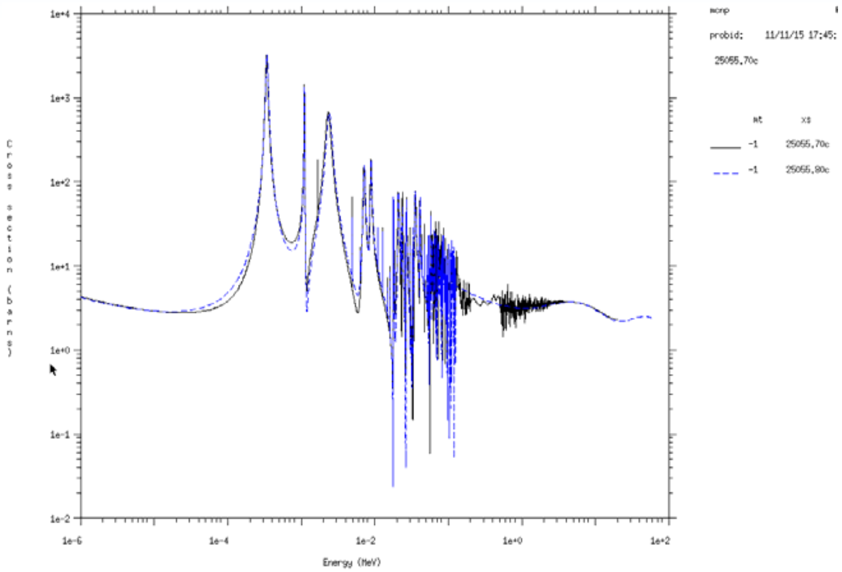


Ni is primary constituent in Haynes-230, in the HPs and bands between core and reflector. Also, Ni in the ~infinite SS-316 shield.

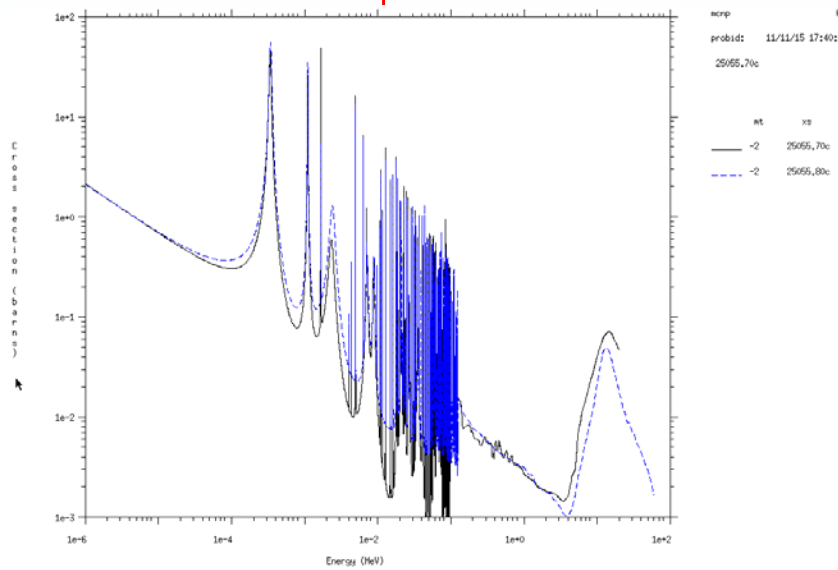
Scatter charts were the same and the absorption chart does not make impact on keff as obvious as the others, but biggest impact could be in

Mn55: Difference ENDF7.0 and 7.1

Total Cross Section Comparison

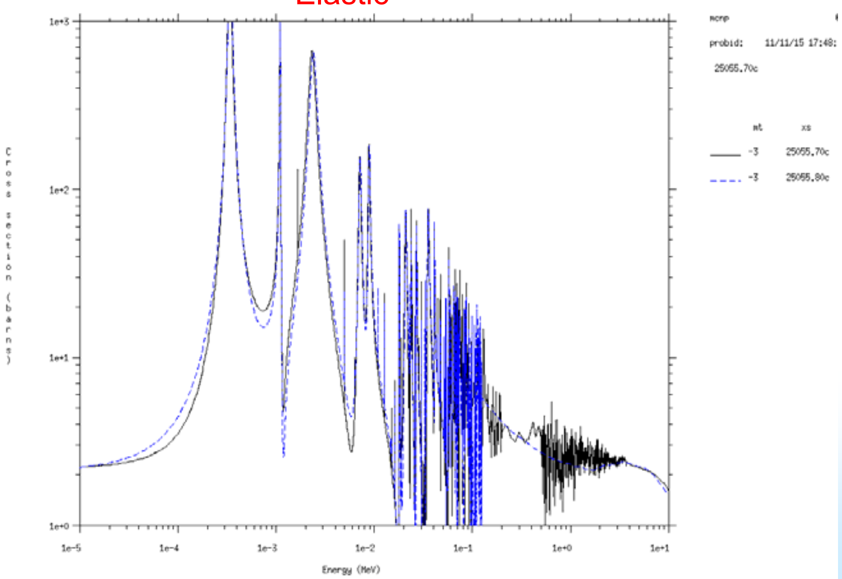


Absorption



Higher capture in epithermal regions causes k-eff to decrease with endf71 (fast difference less important because magnitude of cross section much lower)

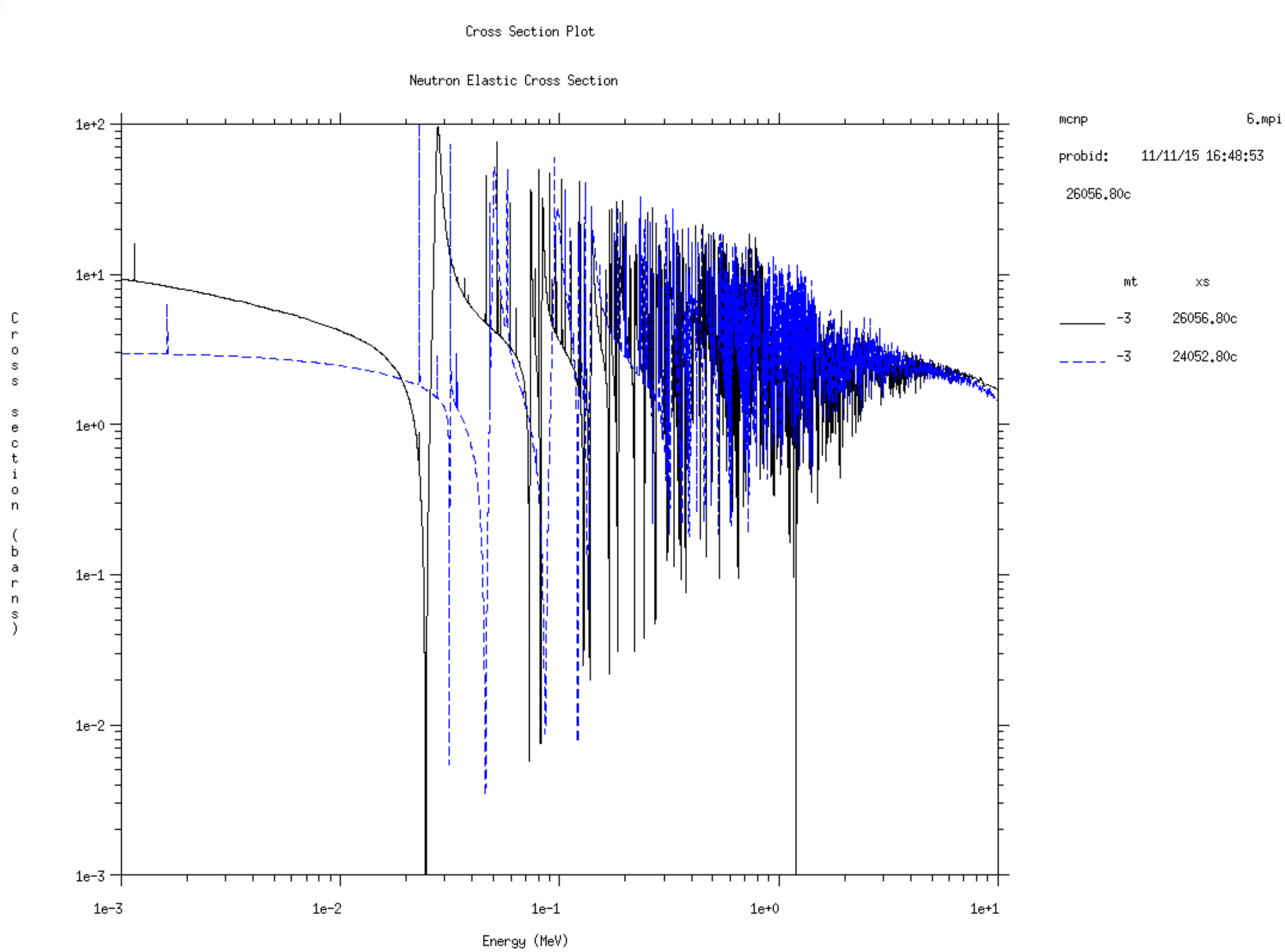
Elastic



Lower fast scatter of endf71 would decrease k-eff (epithermal differences less important).

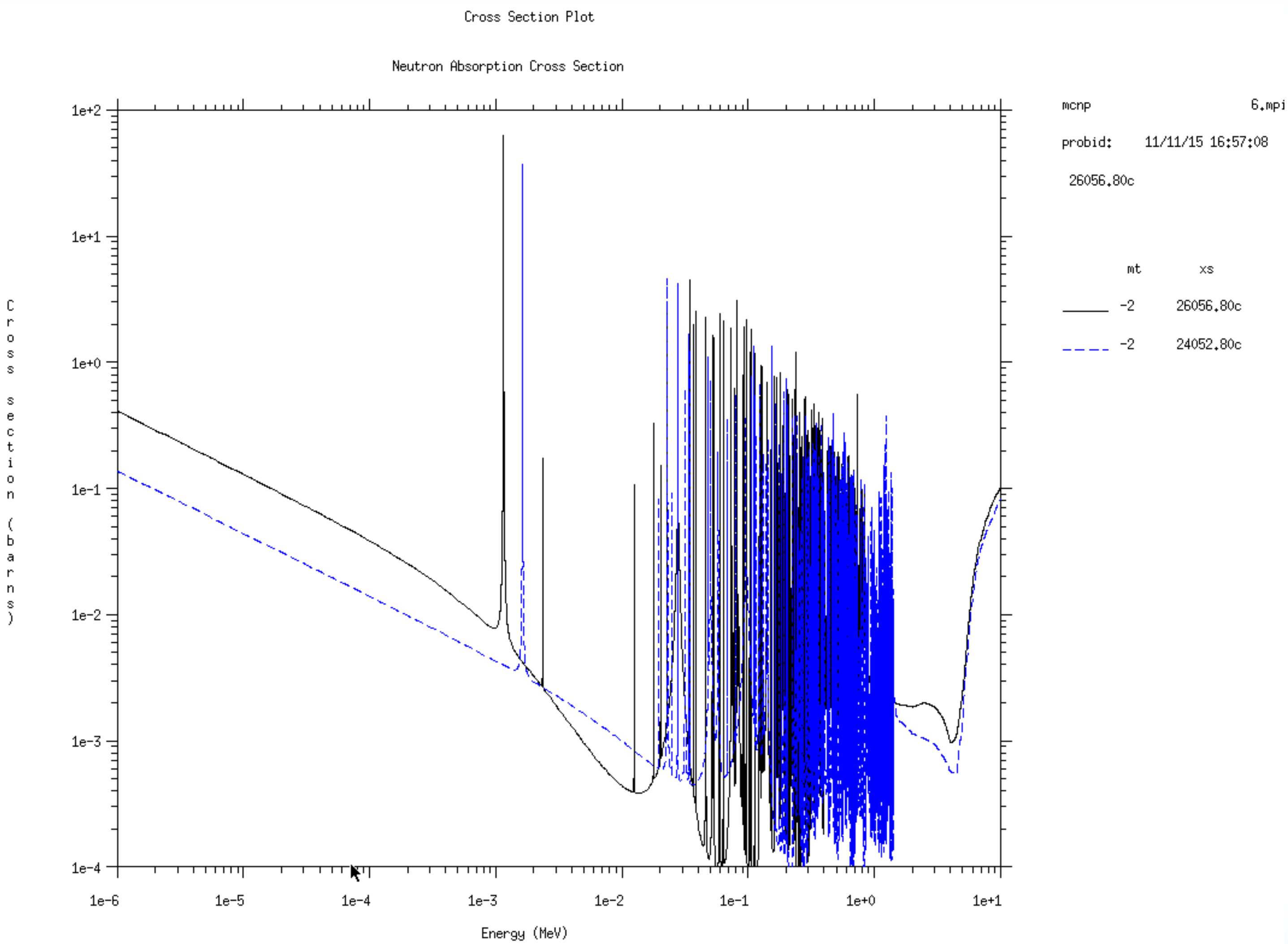
0.5% Mn in Haynes-230 (the HPs and bands between core and reflector). 1.5% Mn in the ~infinite SS-316 shield.

Fe56 vs Cr52 Elastic



Iron is and excellent neutron scatterer, which is why it serves as great reflector and decent shield

Fe56 vs Cr52 Absorption



In addition to being better scatterer, Fe is absorbs far less neutrons that Cr. The neutronic penalty of the Haynes230 is noticeably significant (e.g. when swapping heat pipes or core-clamps.

Potential FRINK improvements

- Implement various impacts that platen position will have on performance
  - Changes in heat transfer from core can due to position of reflector,
  - Changes in component power deposition
  - Change in core power peaking
  - Change in neutron lifetime (effect power spike, but not integral performance)
- More sophisticated operator control simulation
  - Change amount of bump depending on conditions
  - Other inputs like Stirling hot temperature?
- Improved Stirling Model
  - Integrate lookup table - Currently removing power based on Briggs correlation
- Input 2D peaking profile from MCNP – right now axial distribution is hardwired into code
- Possible forced convection option around core can
- Radiation from core inner surface to upper axref, and lower axref (or B4C safety rod if in stack).
- Unmodeled impact of pool in HPs
  - Pool will affect heat transfer across HP to clamp.
  - Maybe add ~5 K delta T from wick to vapor as a function of power
  - Maybe add ~5 K axial delta T from bottom (hot) to top (cold) as function of power
- Option to put HPs anywhere in core
  - Needed for higher-power surface reactor, not KRUSTY
- Coupling of neutron source – which depends on platen position and short-stack value
- Thermal simulators
- Model heater and all of it's associated losses for benchmarking to electrically heated tests